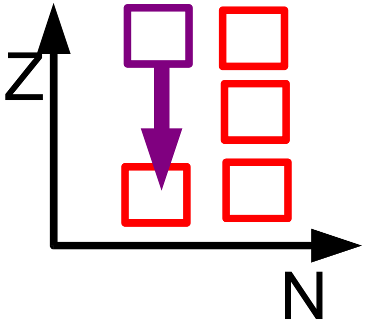
Two-proton radioactivity of ^{45}Fe

Robert Grzywacz
University of Tennessee/ORNL

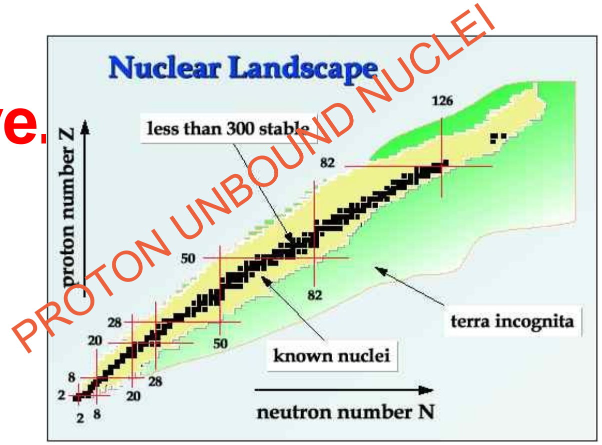
Simultaneous emission of two protons from the ground state of nucleus.



Postulated in 1960 by V.I. Goldansky
Nucl. Phys. 19 (1960) p.482
Nucl. Phys. 27 (1961) p.648

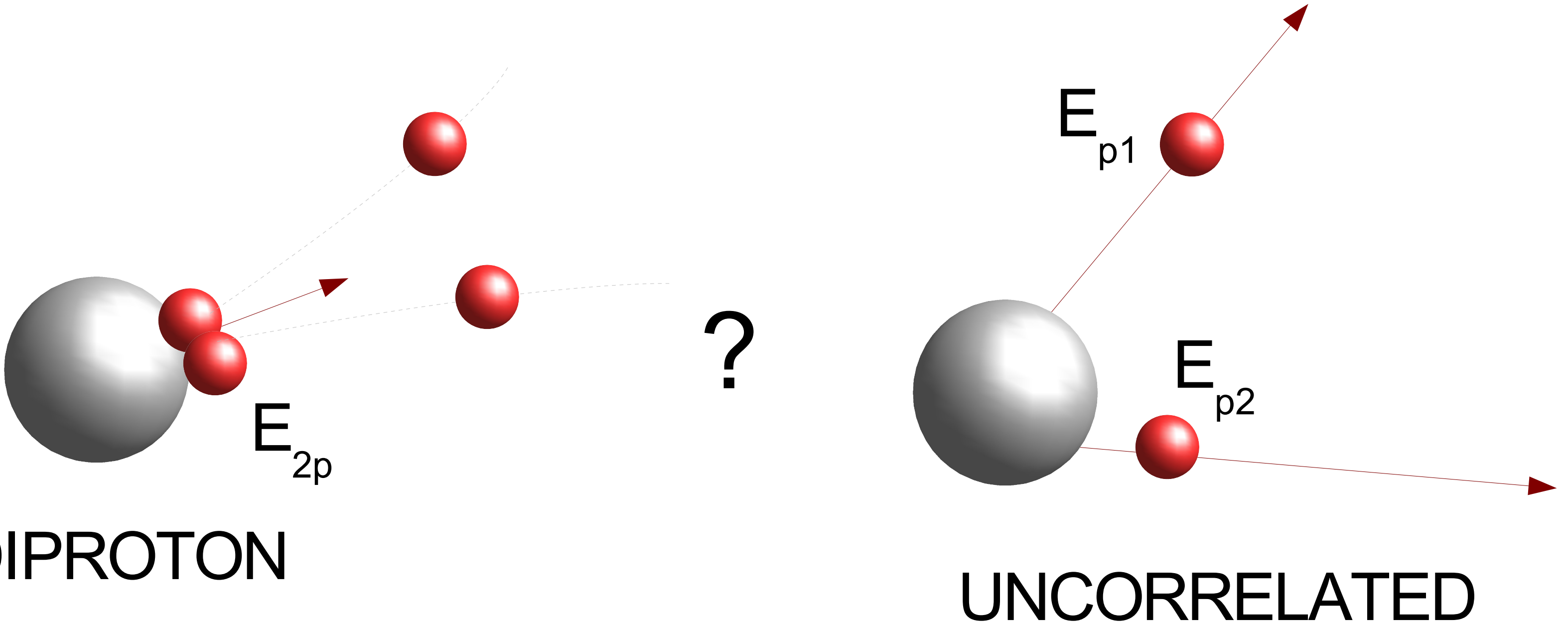
Discovered in 2002
M. Pfützner et al., EPJ A 14 (2002) 279
J. Giovinazzo et al., PRL 89 (2002) 102501

Establish which nuclei are 2p radioactive.



Candidates:
^{19}Mg,^{45}Fe,^{48}Ni,^{54}Zn...

Measure the correlations between emitted protons.

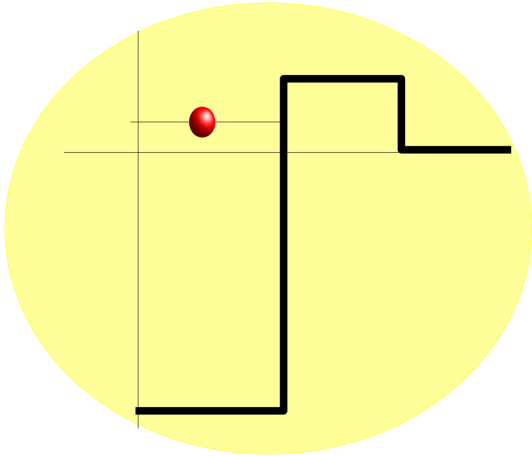


Do nuclear forces keep two protons together ?

(Two) Proton emission:

Tunneling through the potential barrier

$$\lambda = S*\nu*P$$



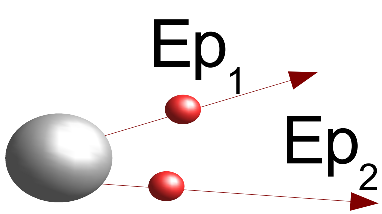
λ – decay probability

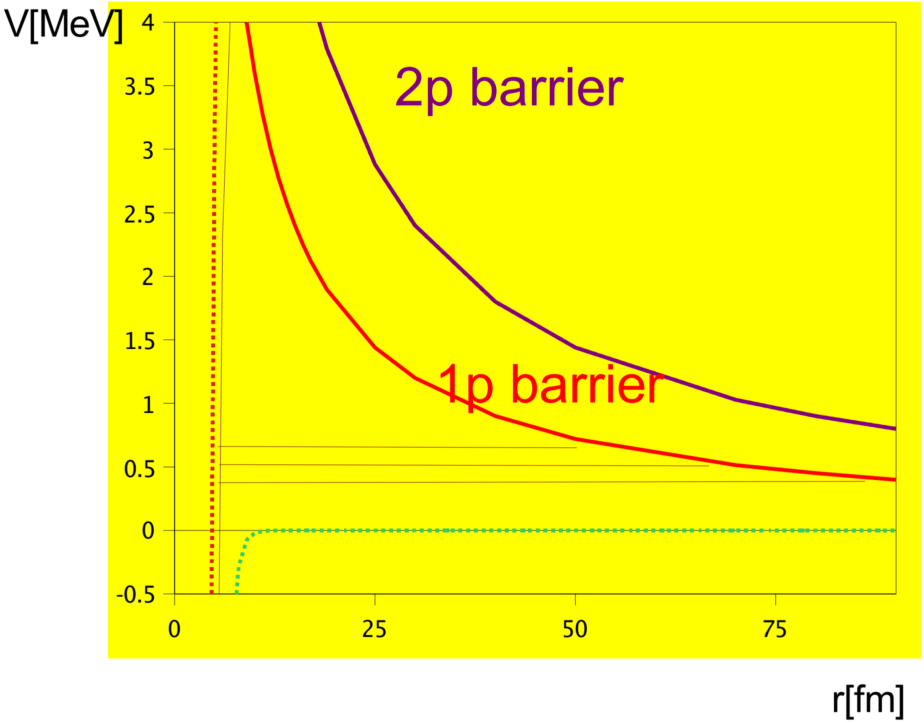
($\lambda \sim 1/T_{1/2}$)

ν – frequency factor

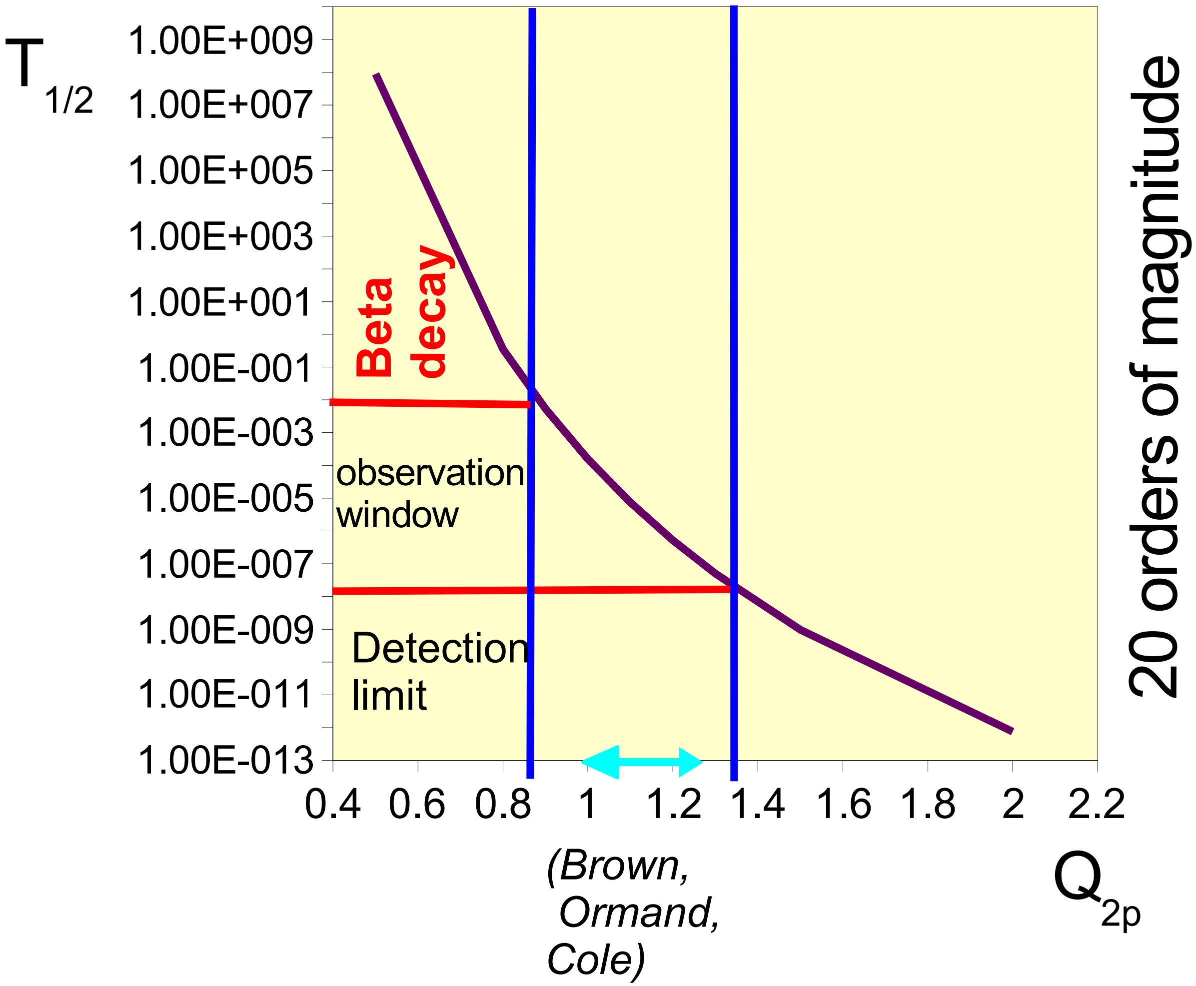
P - barrier penetrability

S - spectroscopic factor





HALF-LIFE SENSITIVITY



Sensitivity from 1 μs to 10 ms required

TWO PROTON DECAY ...

Coulomb barier favors equal energy distribution $E_{p1} = E_{p2}$

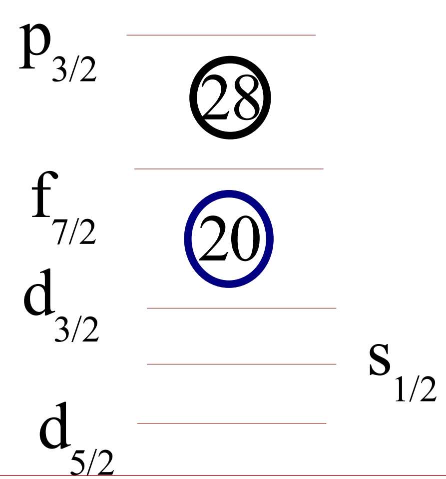
Extremely strong dependance penetrability(2p energy)

Centrifugal barrier favors $l = 0$ “diproton”

Centrifugal barrier suppresses emission of $l > 0$ uncorelated 2p

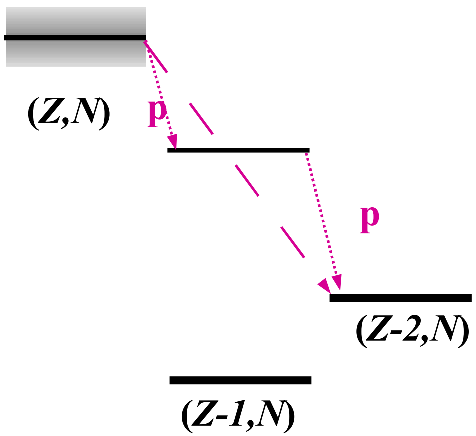
Uncorrelated decay possible from $l = 0$ ($s_{1/2}$) states

$s_{1/2}$ protons unavailable in ^{45}Fe (Z=26)



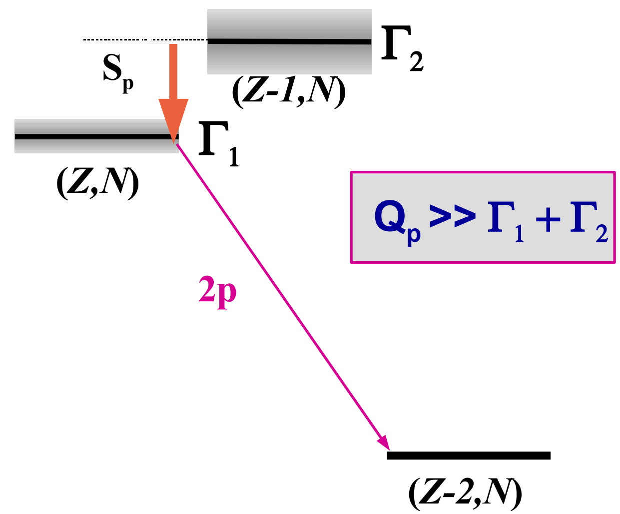
Emission of two protons from nuclear states

SEQUENTIAL



SIMULTANEOUS

uncorrelated vs diproton



sequential decay from excited states

$\Gamma \sim 0.1$ keV, $T_{1/2} \sim 10^{-18}$ s

22Mg*, 26Si* – Cable et al., 1983
35K* – Äystö et al., 1985
31Cl* – Borge et al., 1990
14O* – Bain et al., 1996

2p radioactivity

$\Gamma \sim 10^{-9} - 10^{-13}$ eV , $T_{1/2} \sim 10^{-7}$ -10^{-3} s

Predicted candidates :

^{19}Mg, ^{45}Fe, ^{48}Ni, ^{54}Zn

simultaneous (?) 2p decay from excited state

^{18}Ne* – Gómez del Campo et al., 2000

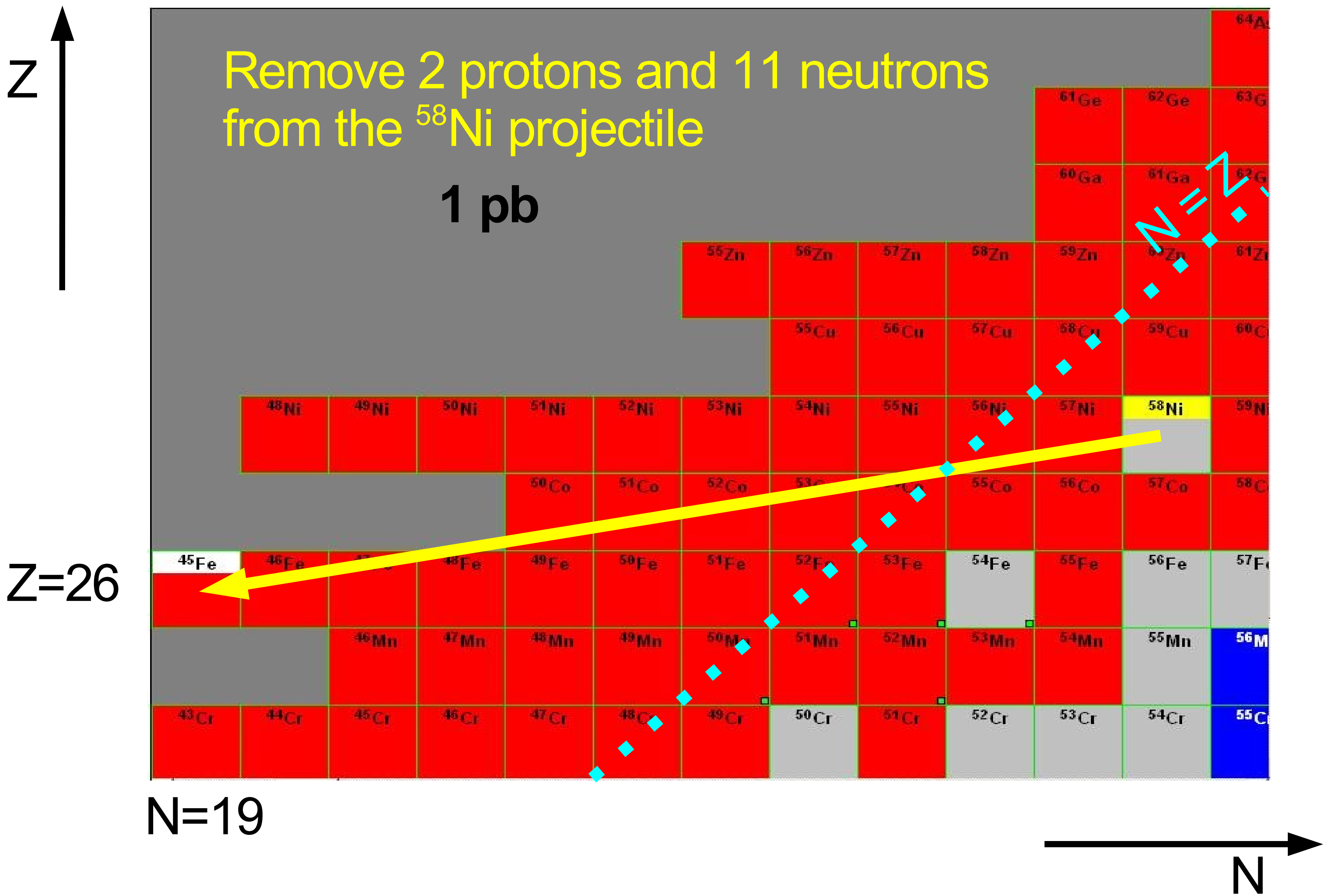
$\Gamma \sim 50$ keV, $T_{1/2} \sim 10^{-20}$ s

Uncorrelated

^{6}Be – Bochkarev et al., 1989

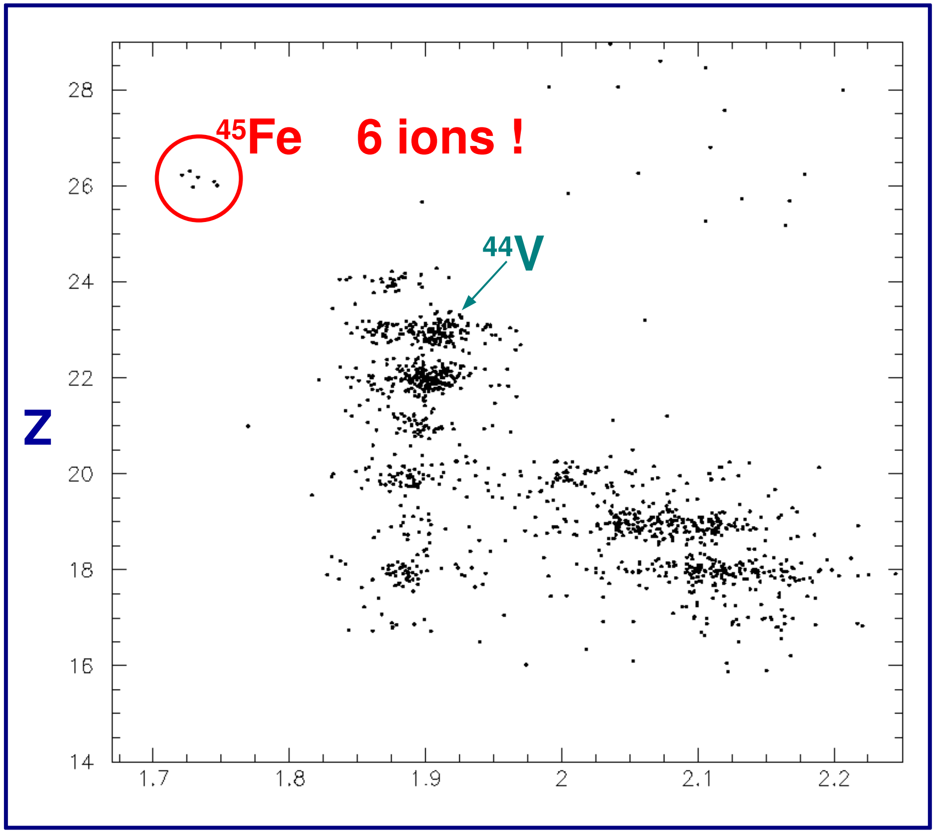
^{12}O – Kryger et al., 1994

^{45}Fe from ^{58}Ni fragmentation



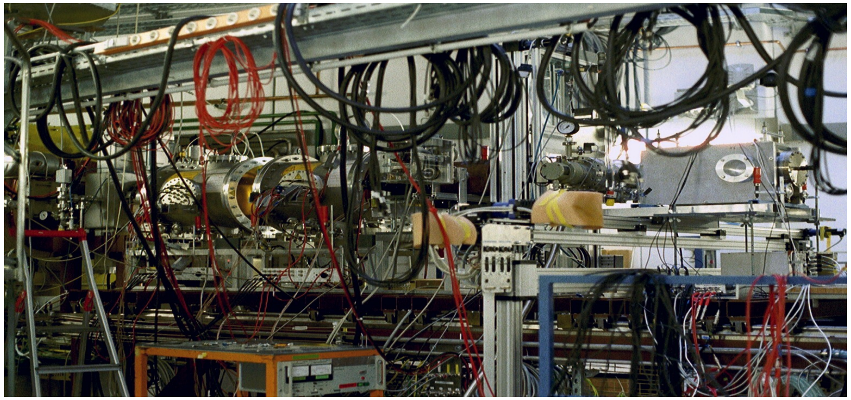
^{45}Fe identification

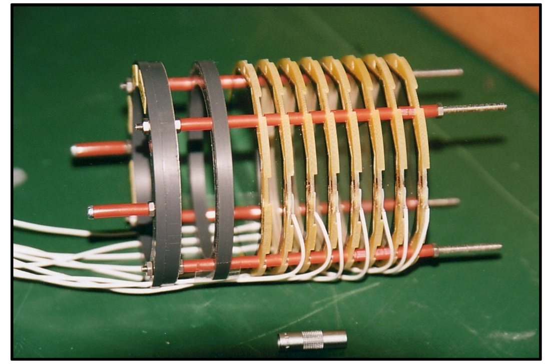
Ions, which triggered acquisition system:
2115 events in 8117 min. (5.6 d)



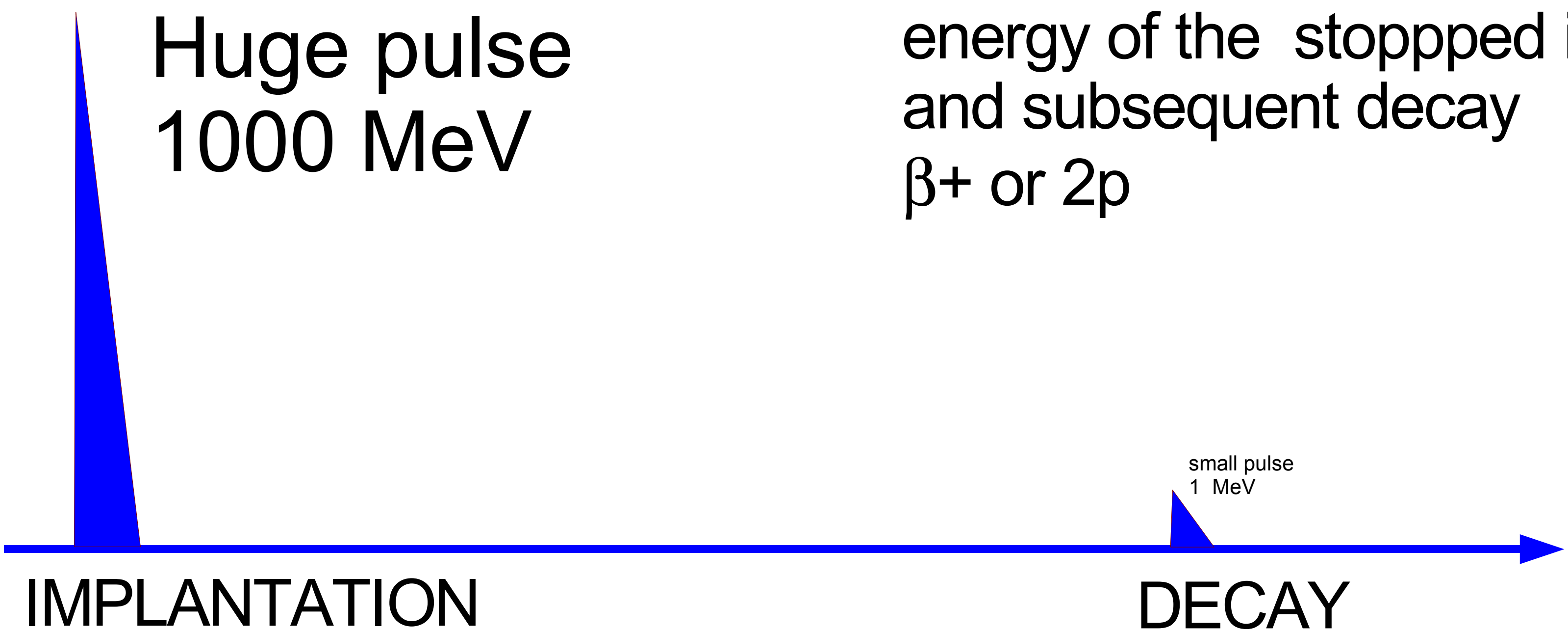
^{45}Fe is very difficult to create !

2 proton decay is very difficult to detect !





Silicon detectors measures the energy of the stoppped ion and subsequent decay $\beta+$ or 2p



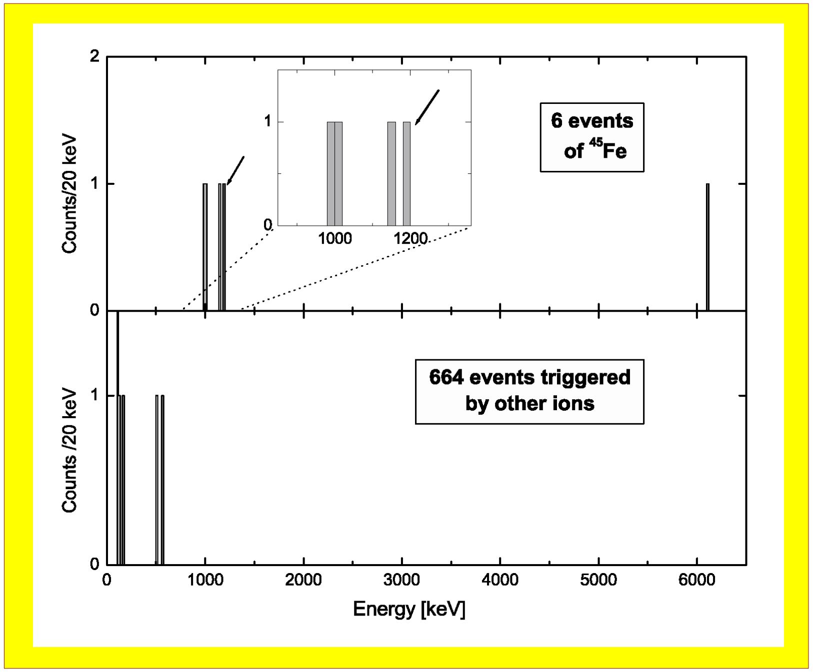
Experimental results:

6 correlated decay events of ^{45}Fe

E(exp) = 1.1 (1) MeV

$$T_{1/2} = 3.2^{+2.6}_{-1.0}\, ms$$

no coincident gamma rays !!!!



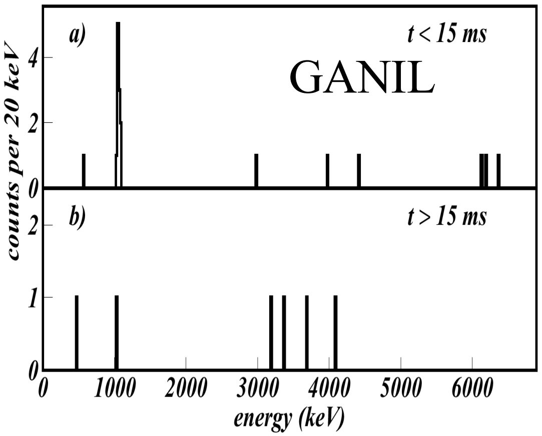
*M. Pfützner. et al., EPJA **14**, 279 (2002)*

E and $T_{1/2}$ consistent with 2p decay

results from experiment at GANIL (FRANCE)

E(exp) = 1.14 (4) MeV

$$T_{1/2} = 4.7^{+3.4}_{-1.4}\, ms$$



J. Giovinazzo et al. Phys. Rev. Lett. 89 (2002) 102501

2p decay of ^{45}Fe – summary of results

GSI: Fragmentation of ^{58}Ni beam @ 650 MeV/u

6 ^{45}Fe ions implanted in a stack of Si detectors

M. Pfützner et al., EPJ A 14 (2002) 279

M. Pfützner et al., NIM A 493 (2002) 155

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

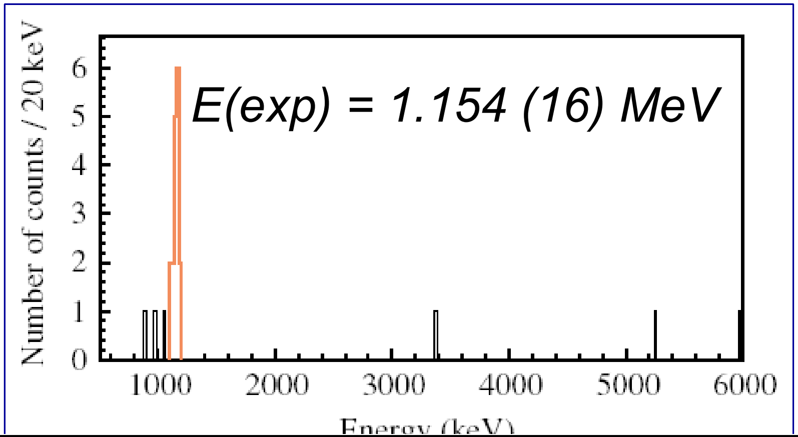
22 ^{45}Fe ions implanted in a Si strip detector

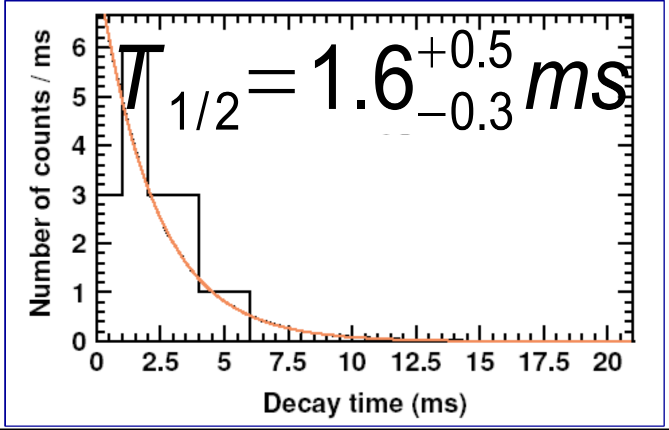
J. Giovinazzo et al., PRL 89 (2002) 102501

New data (also discovery of 2p emission in ^{54}Zn and ^{48}Ni)

2nd GANIL experiment:

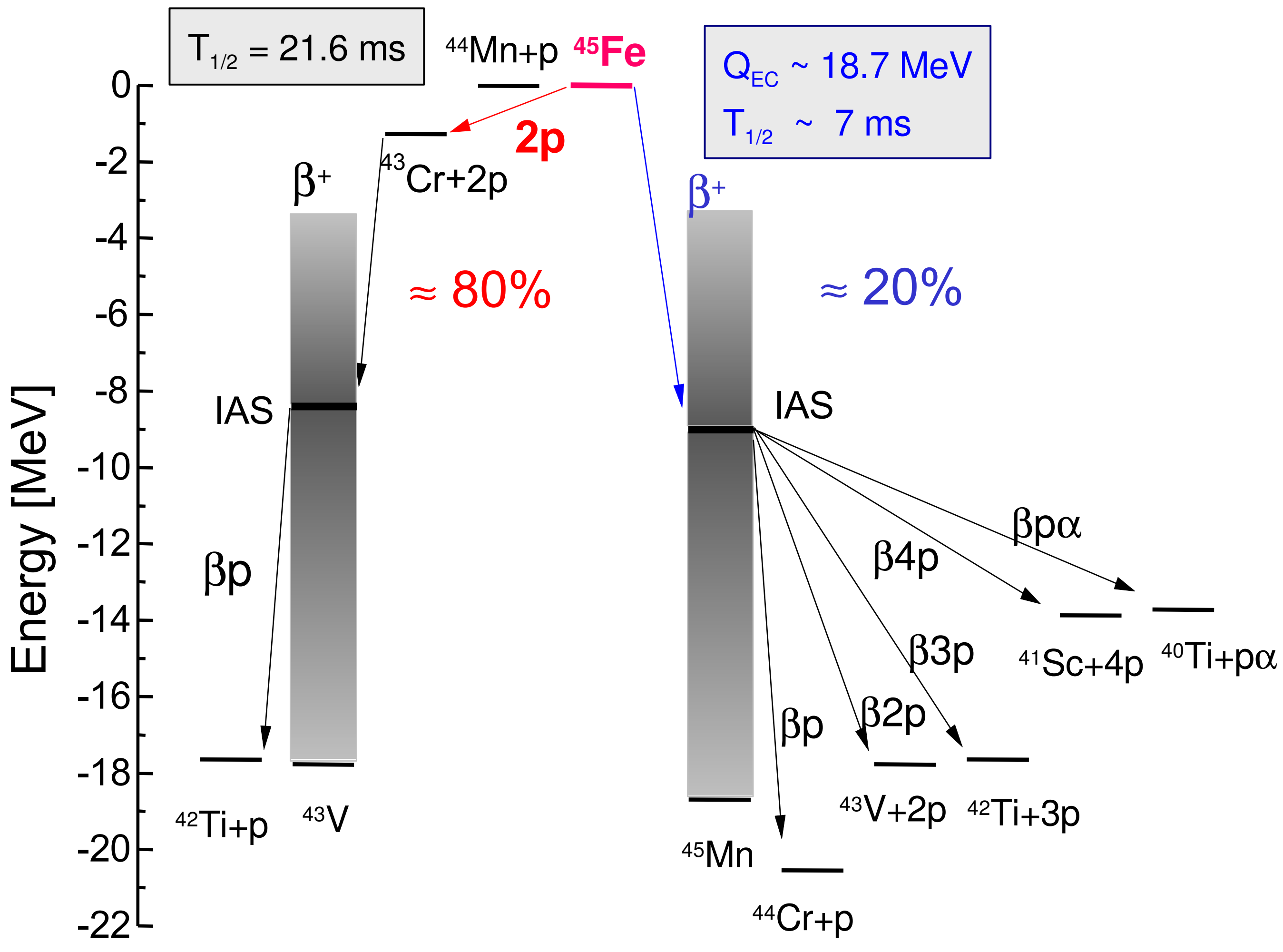
C. Dossat et al., PRC 72 (2005) 054315



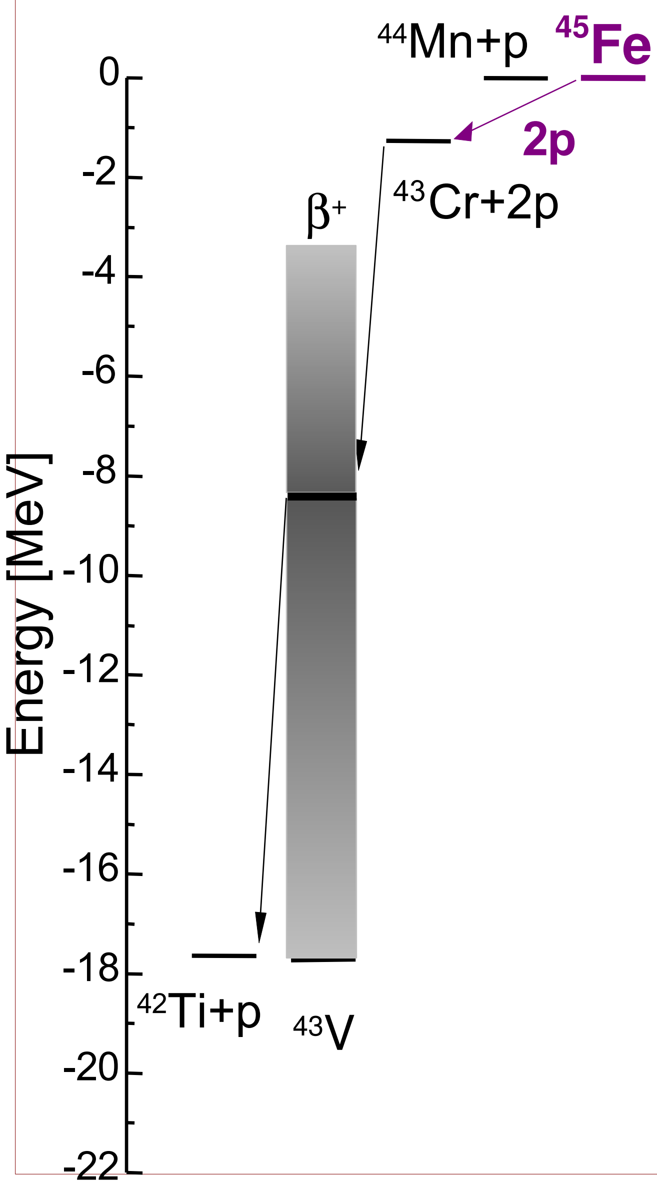


	2p decay energy (MeV)	Half-life (ms)	Branching ratio	Partial half-life (ms)
Giovinazzo *et al.* [5]	1.140 ± 0.040	$4.7^{+3.4}_{-1.4}$	0.55 ± 0.12	$8.5^{+6.4}_{-3.2}$
Pfützner *et al.* [6]	1.1 ± 0.1	$3.2^{+2.6}_{-1.0}$	$0.80^{+0.15}_{-0.25}$	$4.0^{+3.3}_{-1.8}$
This work	1.154 ± 0.016	$1.6^{+0.5}_{-0.3}$	0.57 ± 0.10	$2.8^{+1.0}_{-0.7}$
Average	1.151 ± 0.015	$1.75^{+0.49}_{-0.28}$	0.59 ± 0.07	$3.0^{+0.9}_{-0.6}$

^{45}Fe decay scheme



POSSIBLE DECAY MODES OF ^{45}Fe



two proton emission

$$^{45}_{26}Fe_{19} \xrightarrow{2p} {}^{43}_{24}Cr_{19}$$

$-1000\ keV < S_{2p} < -1300\ keV$

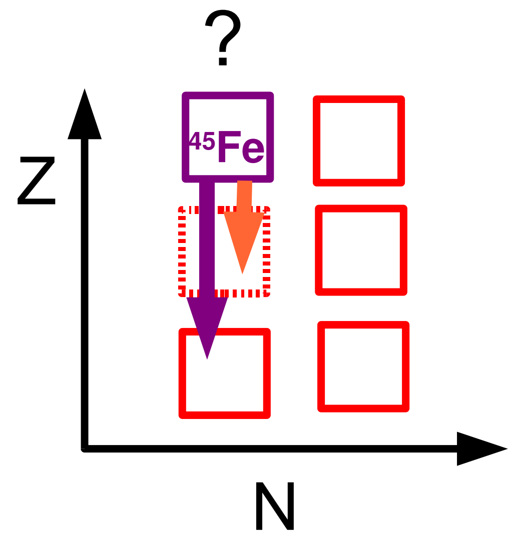
$T_{1/2} \sim 10^{-6} - 1\ s$

single proton emission

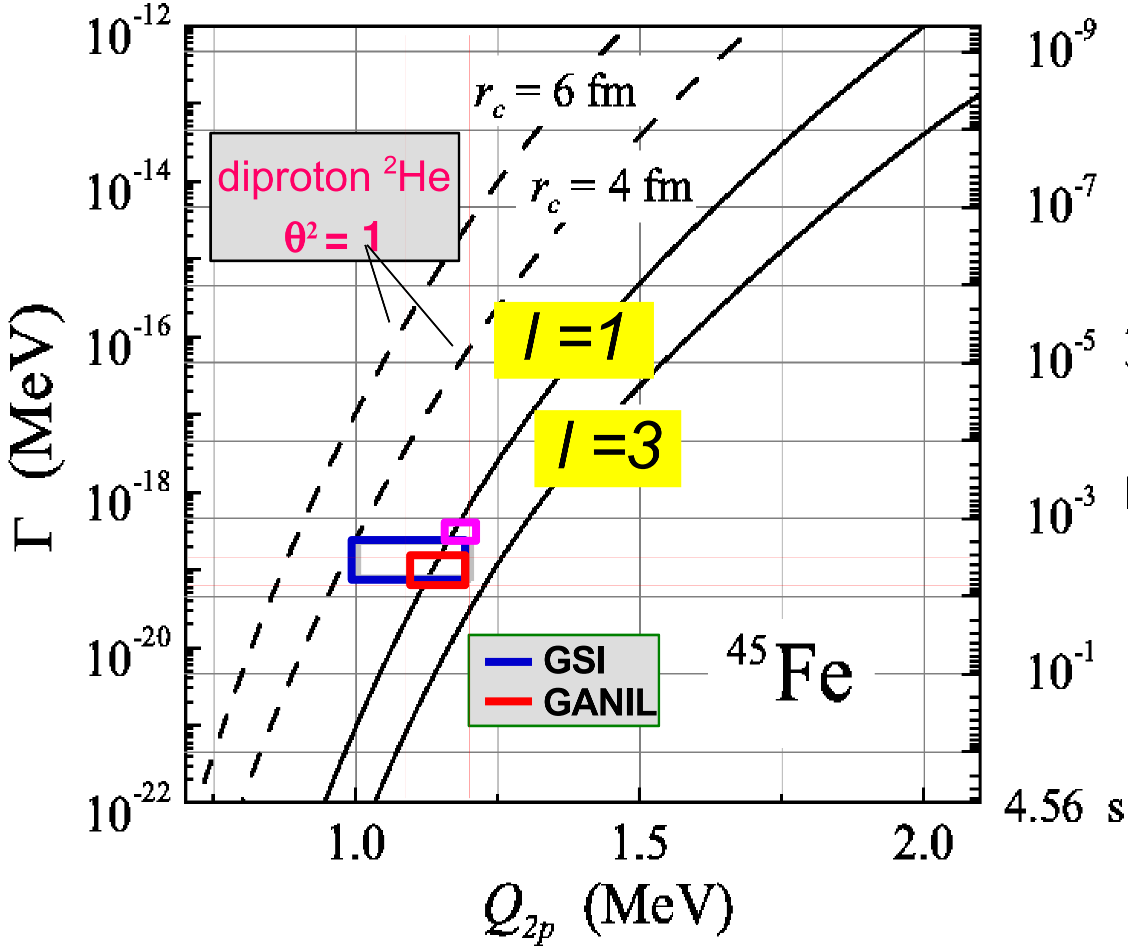
$$^{45}_{26}Fe_{19} \xrightarrow{p} {}^{44}_{25}Mn_{19}$$

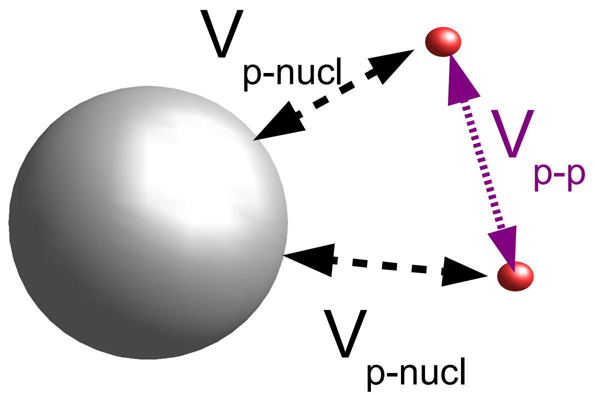
$-120\ keV < S_p < 70\ keV$

$T_{1/2} > 100\ s$



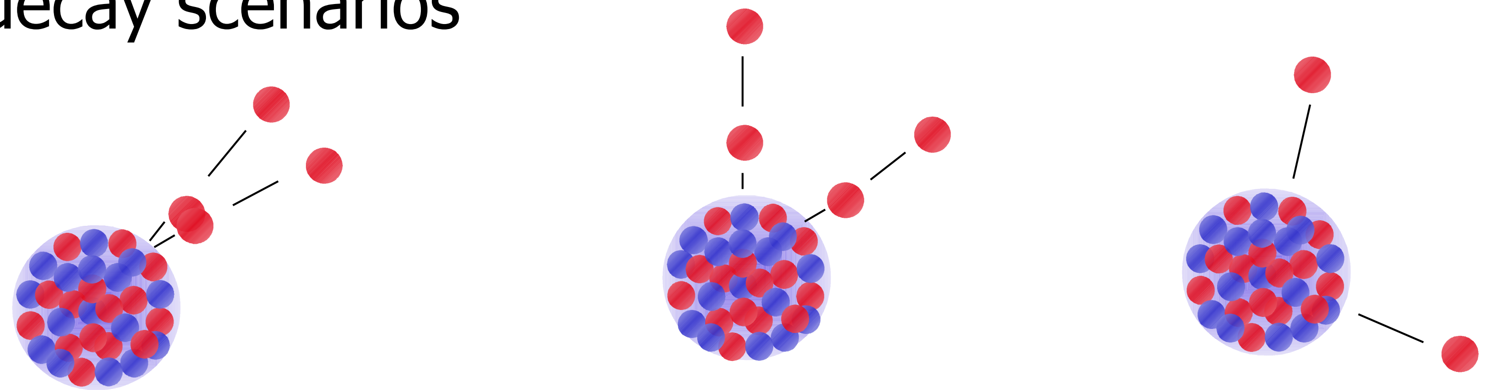
2p decay of ^{45}Fe in a three-body model

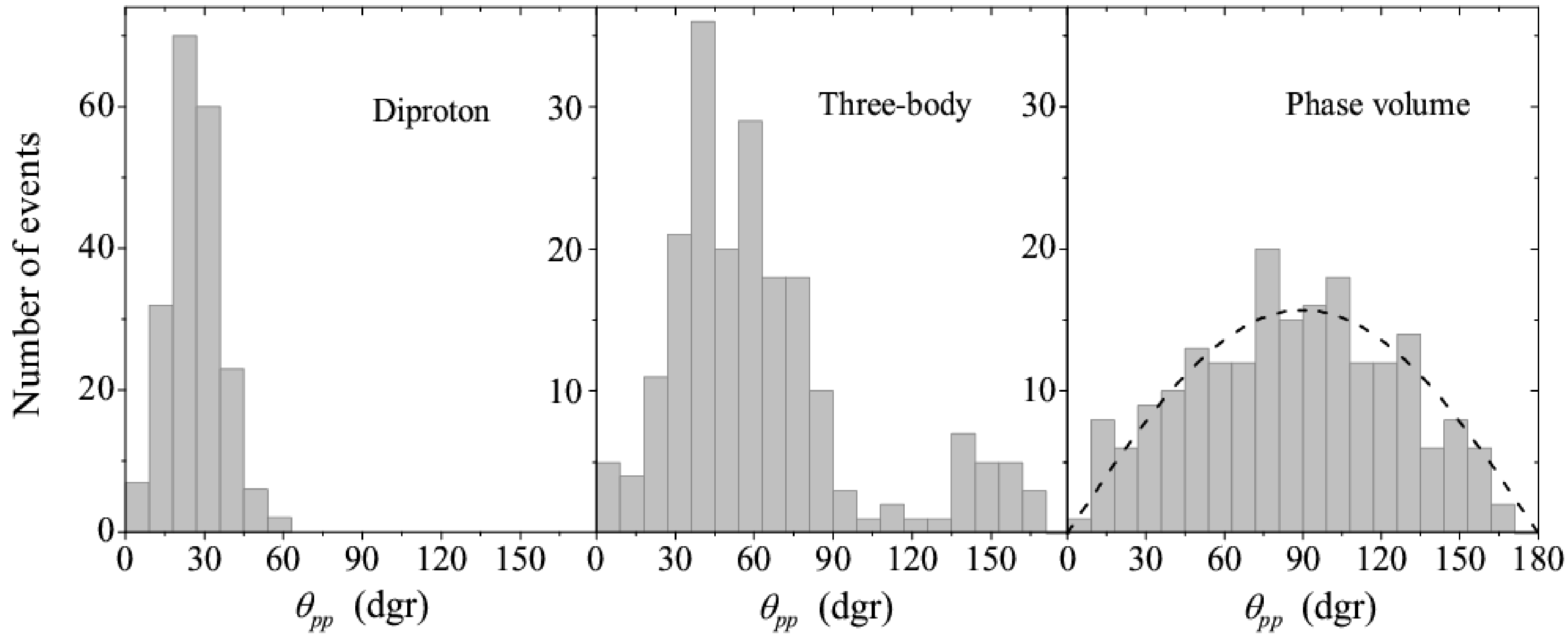




L. Grigorenko et al.
Phys. Rev. Lett. 85(2000) 22
Nucl. Phys. A 714(2003) 425

2p decay scenarios





The Monte-Carlo simulations (200 events) of the opening angle pp between the protons emitted in the decay of 45Fe.

L. Grigorenko

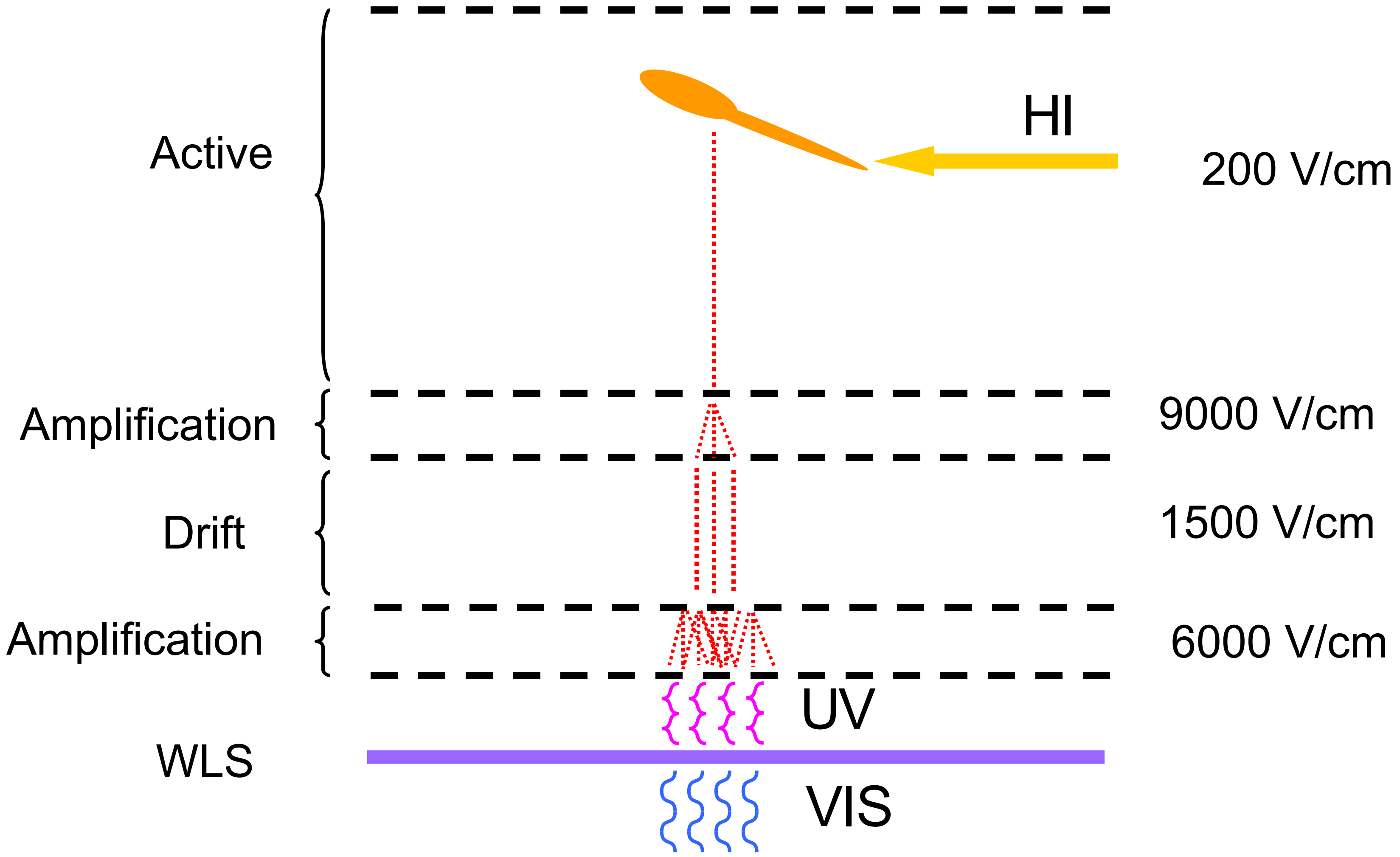
Optical **T**ime **P**rojection **C**hamber

Gaseous ionization detector developed to measure the angular and energy correlations between the protons emitted in 2p decay of ^{45}Fe.

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

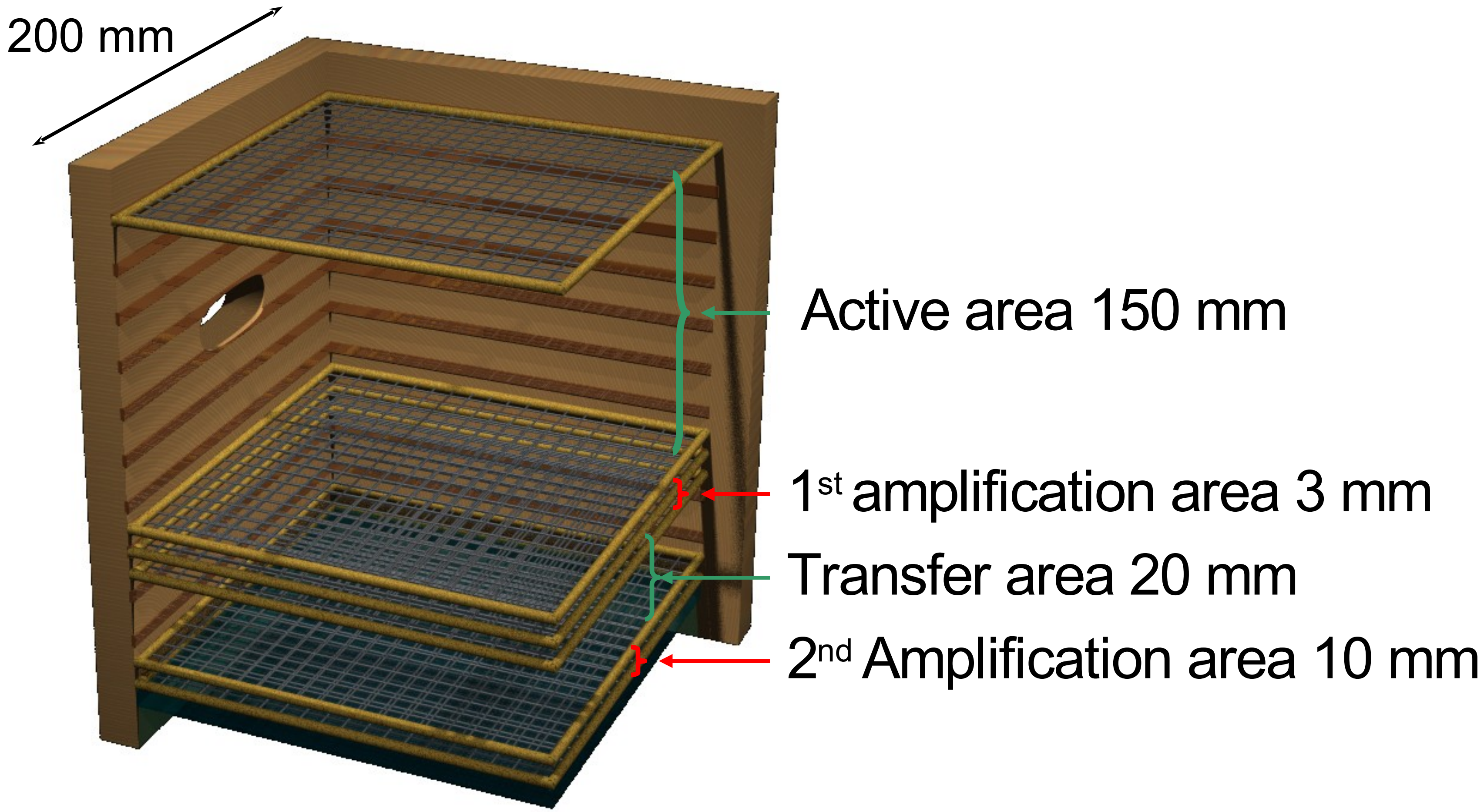
^{45}Fe concept: W. Dominik (2002)

Optical Time Projection Chamber operation principle



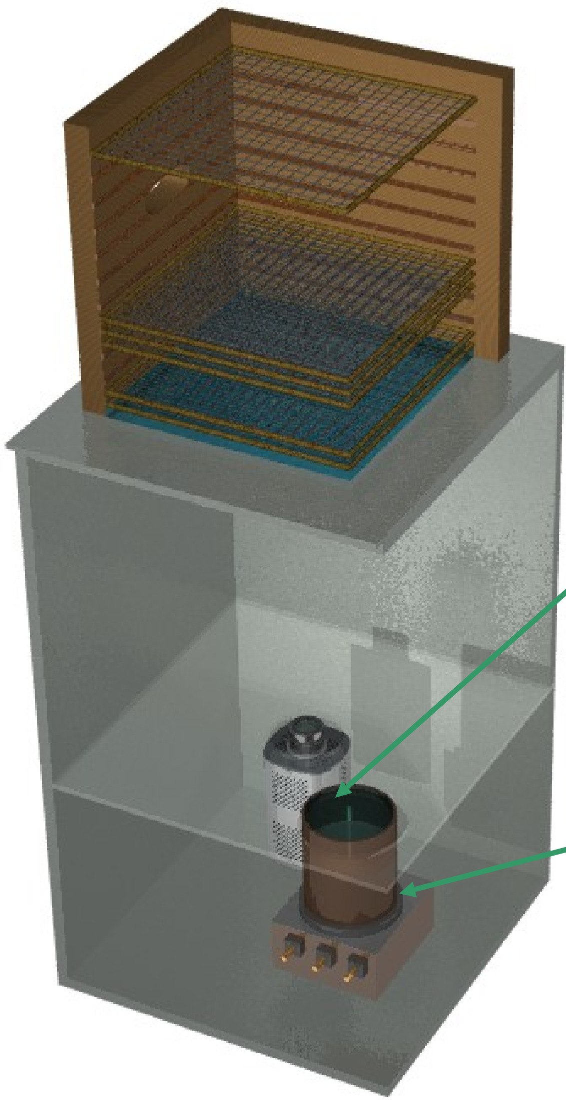
Optical Time Projection Chamber

Gas (1 atm) : 49% He + 49% Ar + 1% N_2 + 1% CH_4

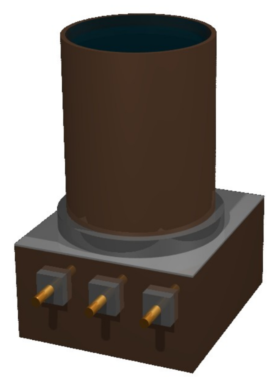


K. Miernik

Optical Time Projection Chamber

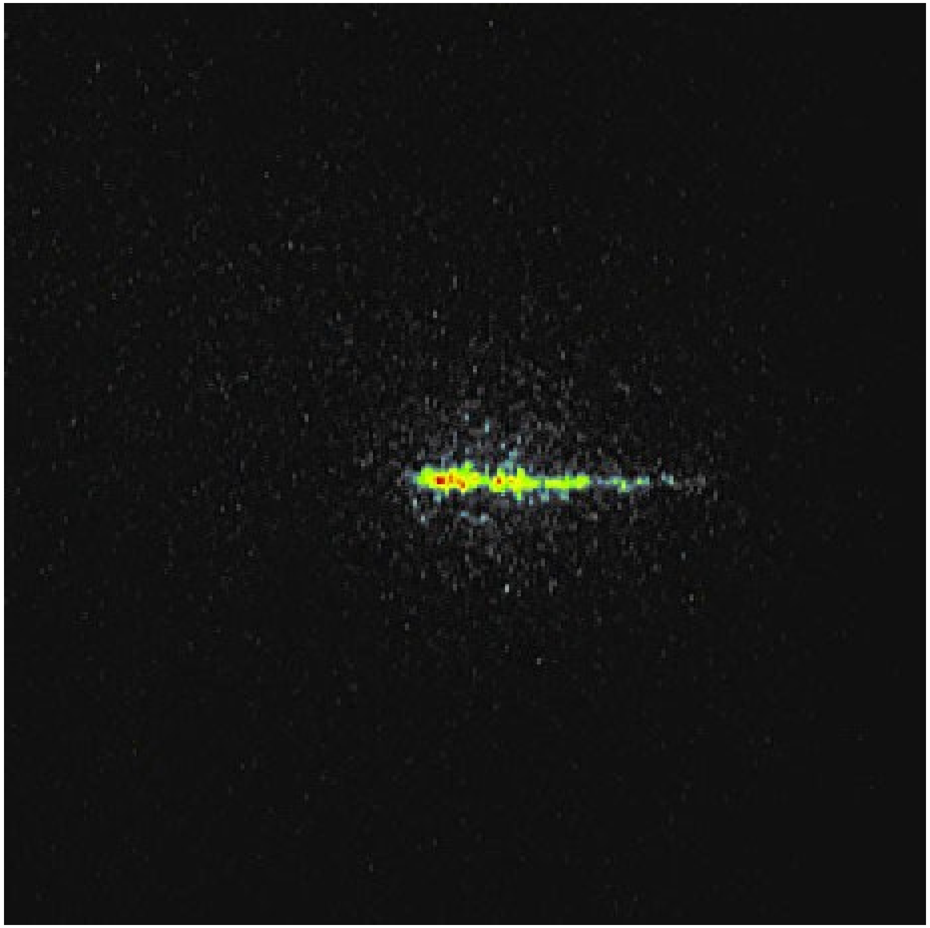


CCD Camera
- 1000x1000 pix
- 12-bits
- image amplification (x2000)



Photomultiplier 5''

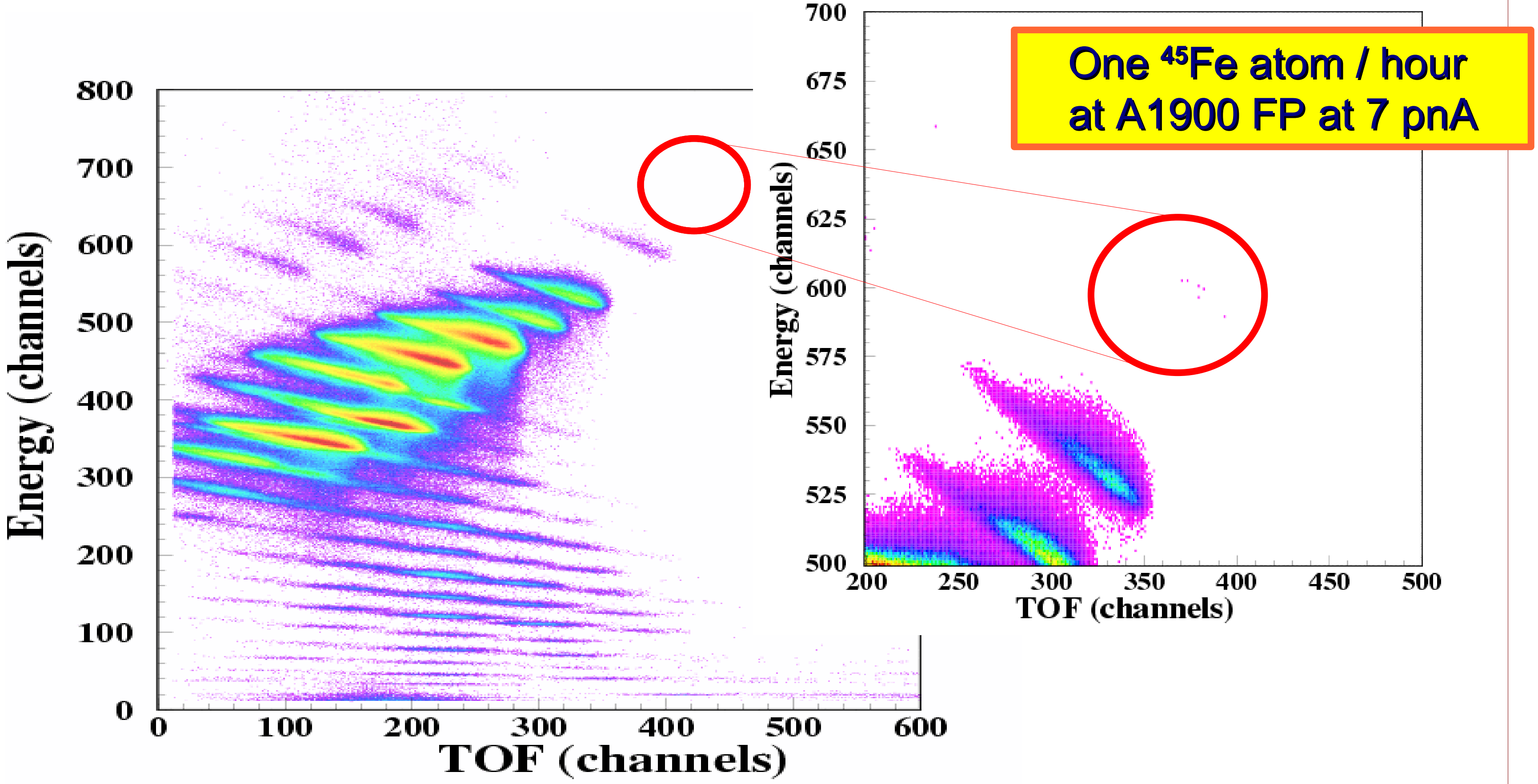
K. Miernik



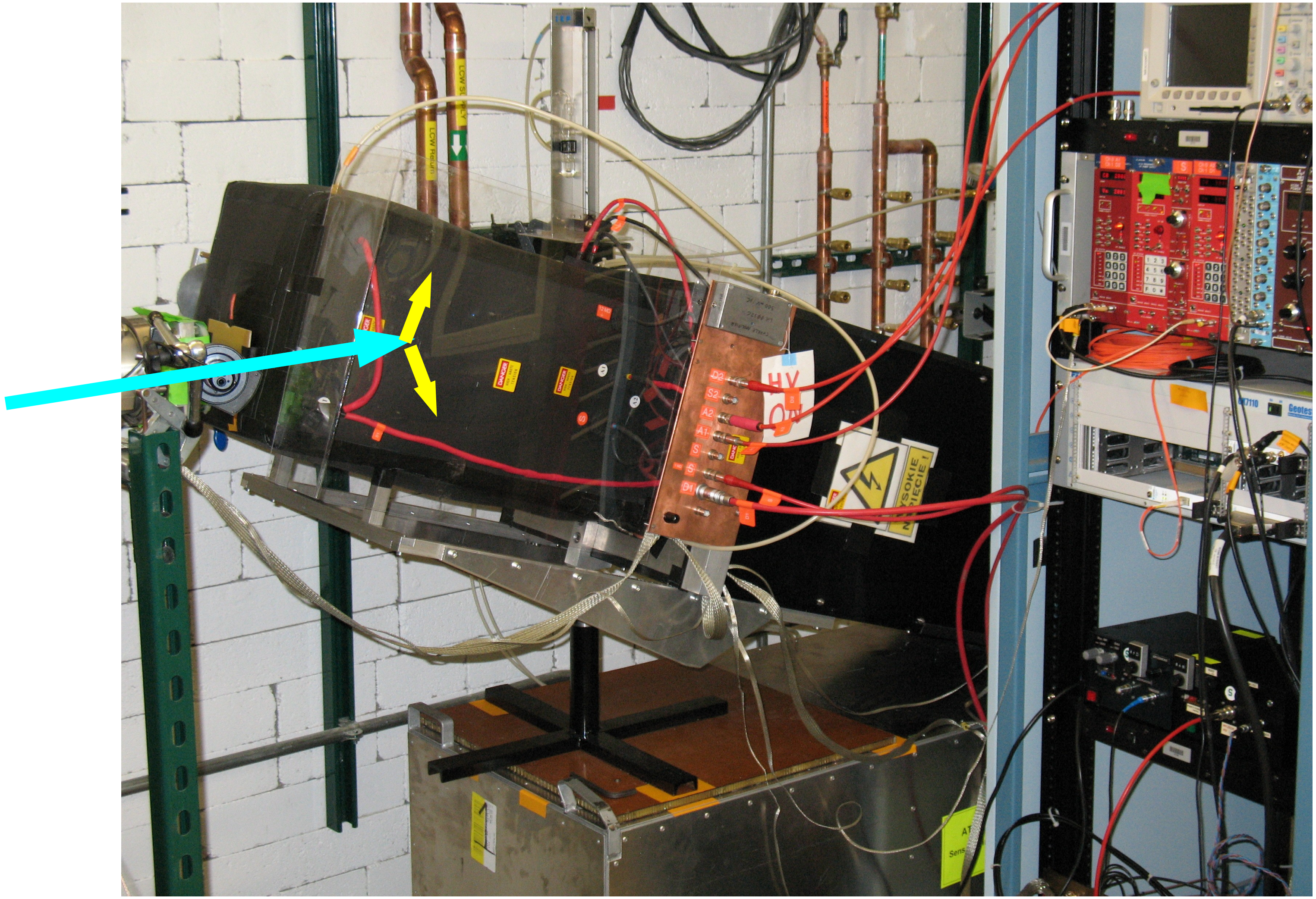
The 2-D image of a single track recorded with a CCD camera after 1 ms exposure.
The track length is 54 mm in agreement with the range of 4.5 MeV particle in the gas mixture of 49.5% Ar + 49.5% He + 1% N2 .

Test at NSCL : Production of ^{45}Fe

Setting for ^{45}Fe: particle ID at the A1900 I4 focal plane, full acceptance Δp/p=4%. 800 mg/cm² Ni target

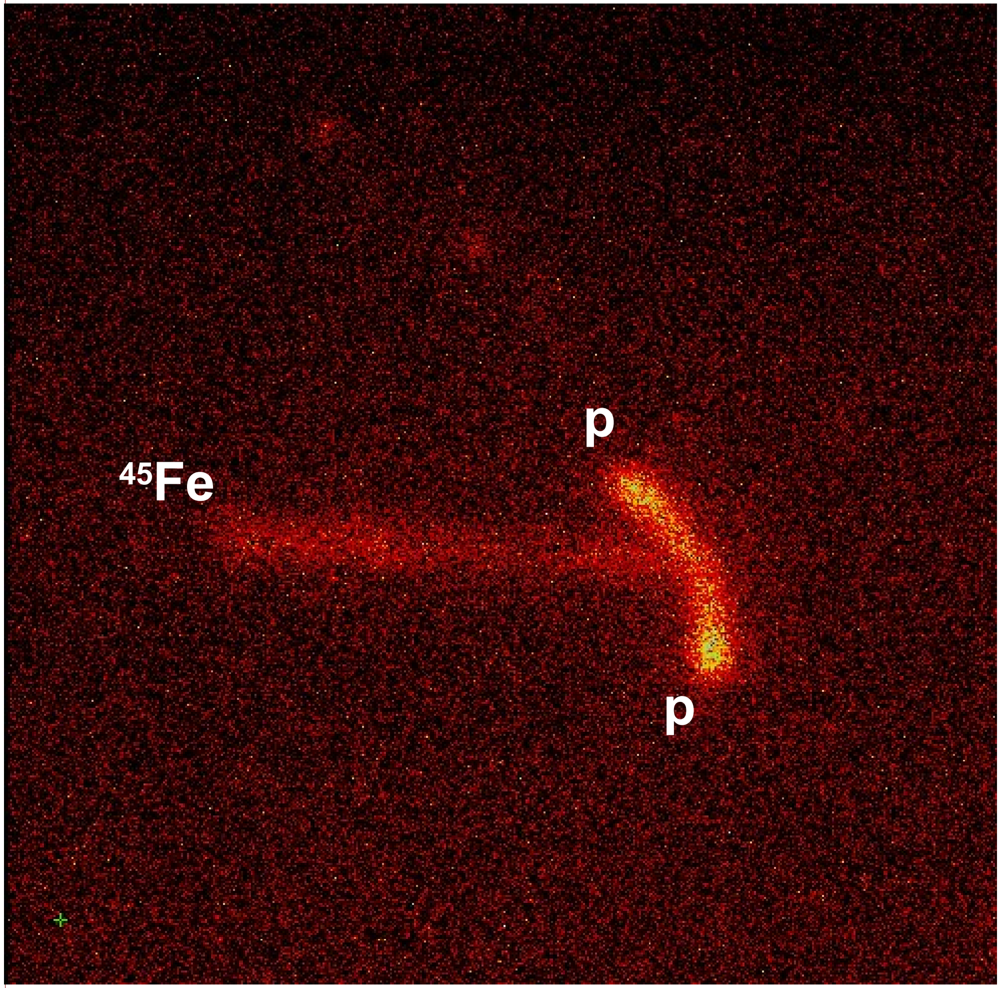


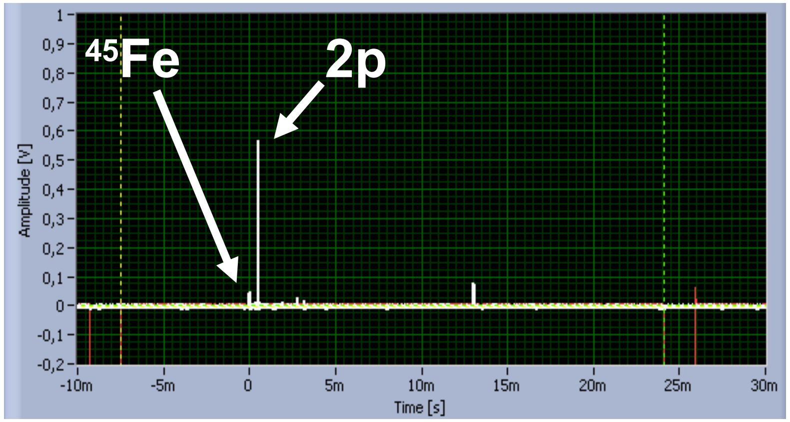
OTPC at NSCL

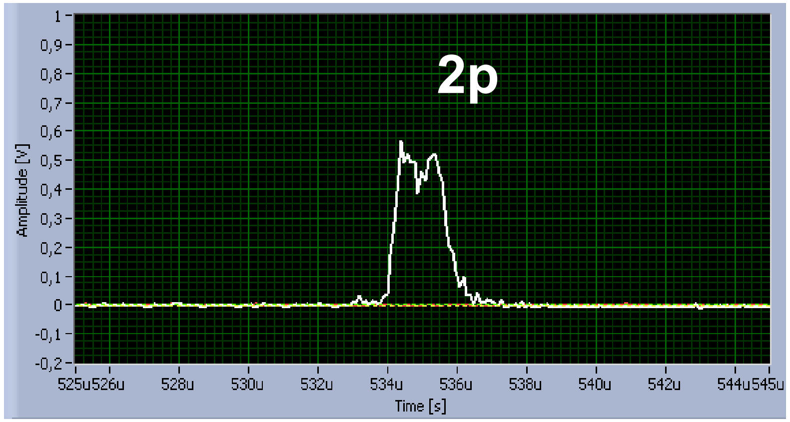


^{45}Fe 2p decay measurements 2 Feb 2007 – 11 Feb 2007

2p decay of ^{45}Fe



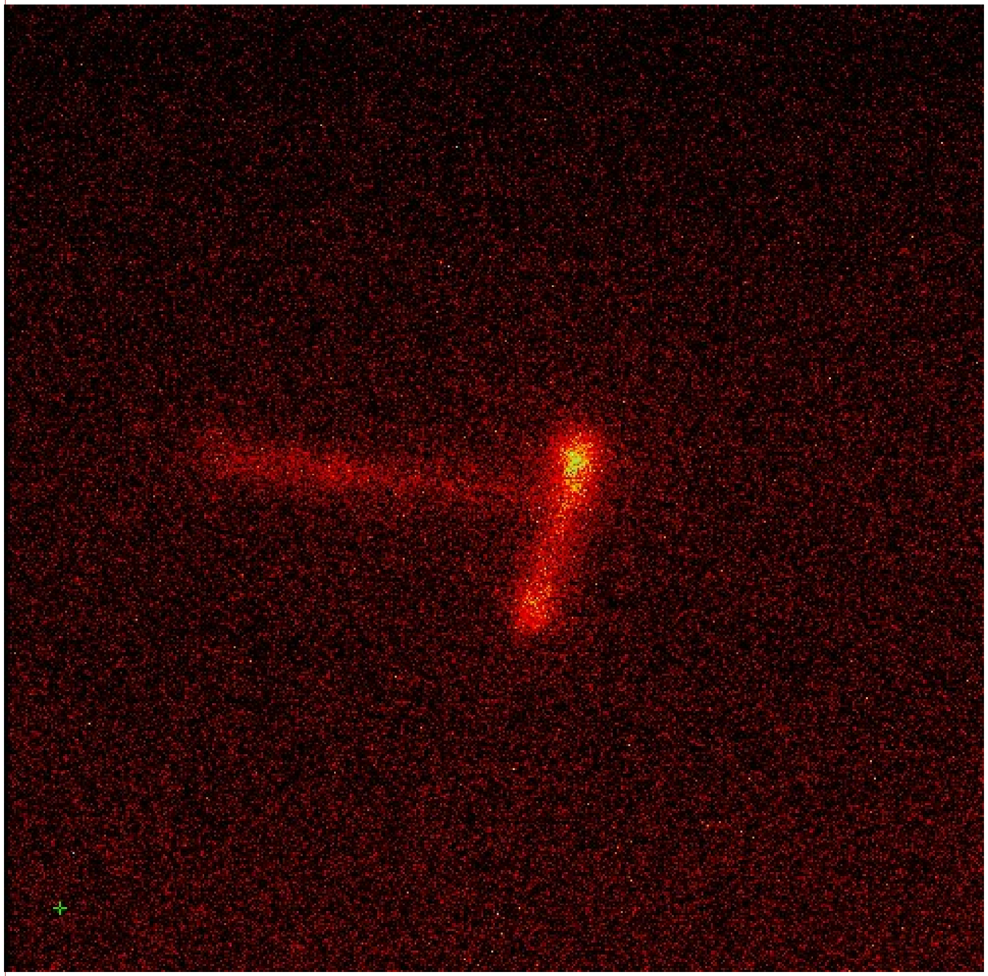


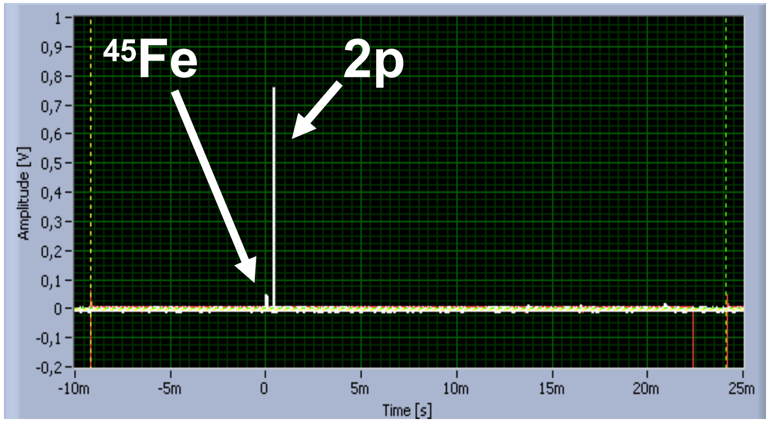


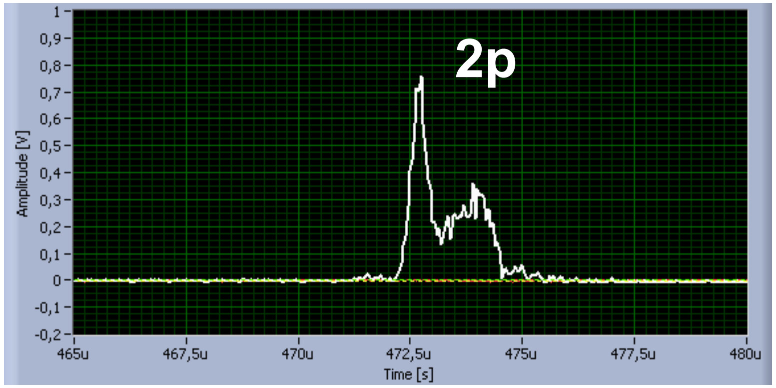
2p decay 0.53 ms after implantation

K. Miernik

2p decay of ^{45}Fe



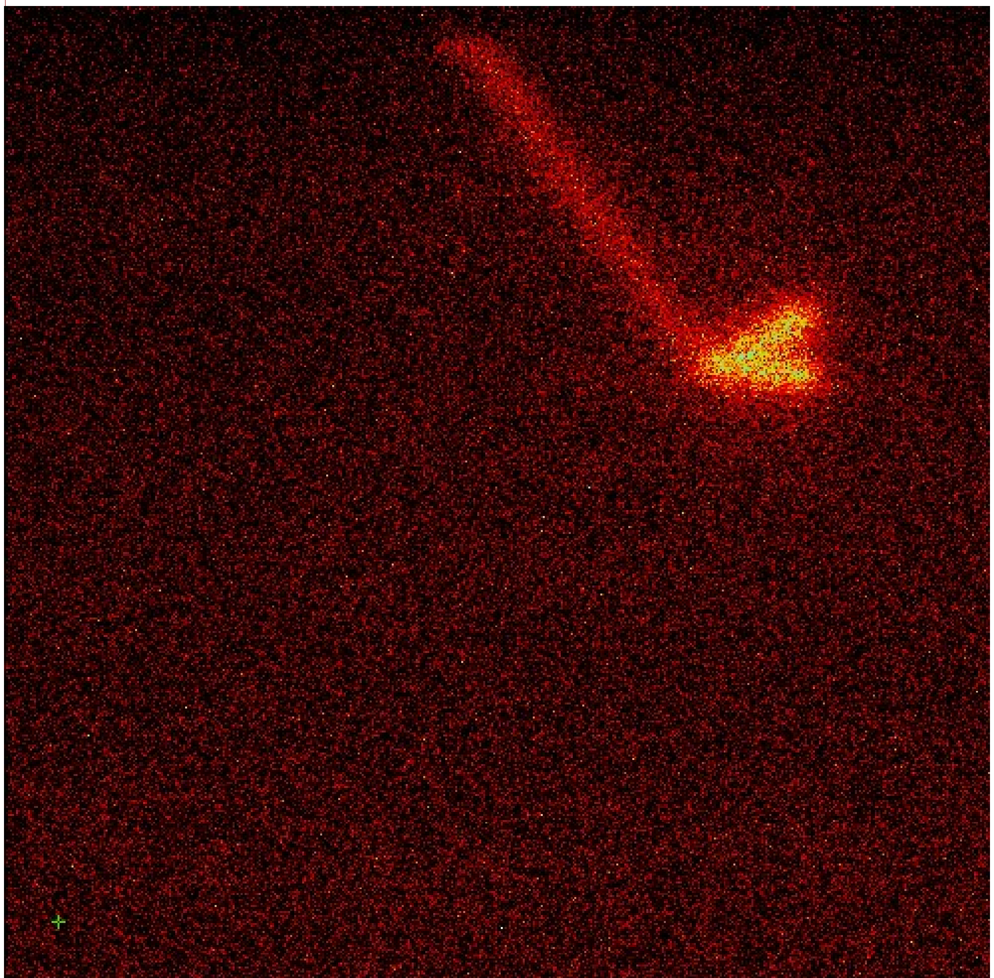


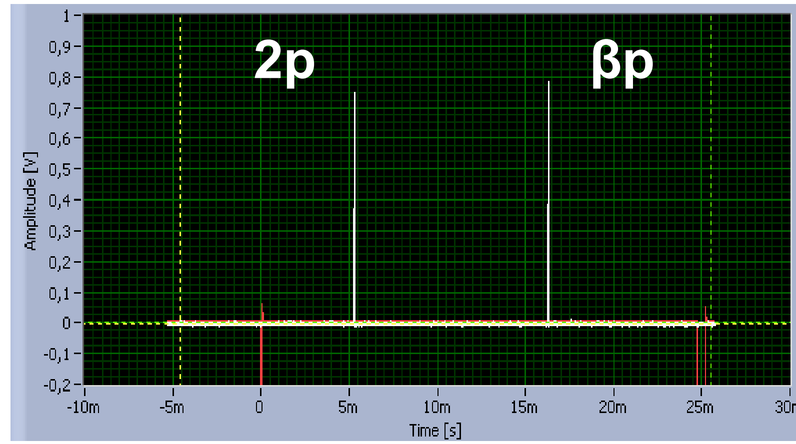


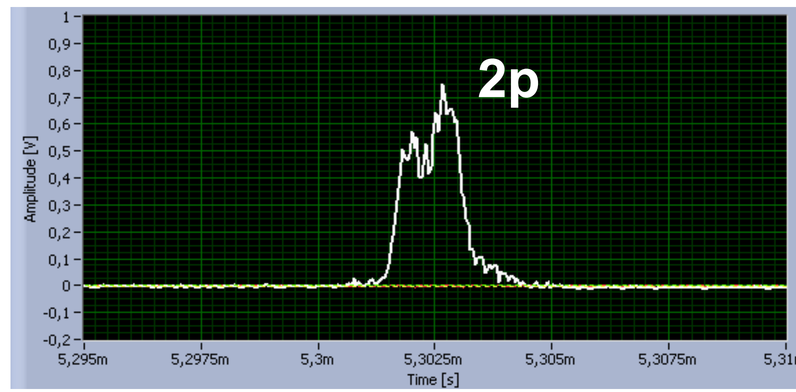
2p decay 0.47 ms after implantation

K. Miernik

2p decay of ^{45}Fe







2p decay 5.3 ms after implantation

K. Miernik

Summary

Two proton radioactivity of 45Fe

- Two proton emission was expected in ^{45}**Fe**
- Barrier effects are favoring correlated emission
- Advanced theory: true three body correlations

- Clear evidence for the **2p** radioactivity in ^{45}**Fe**
- Remarkable agreement of E_{2p} with predictions !
- $T_{1/2}$ compatible with calculations
- **Experiment at NSCL with OTPC – pp correlation !**

This is only a beginning of fascinating research

The Collaboration

Warsaw University
- H. Czyrkowski
- M. Ćwiok
- W. Dominik
- Z. Janas
- M. Karny
- A. Korgul
- K. Miernik
- M. Pfützner

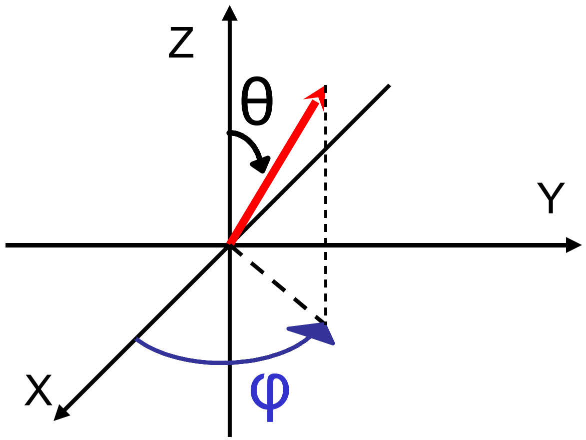
Oak Ridge National Laboratory
- K. Rykaczewski

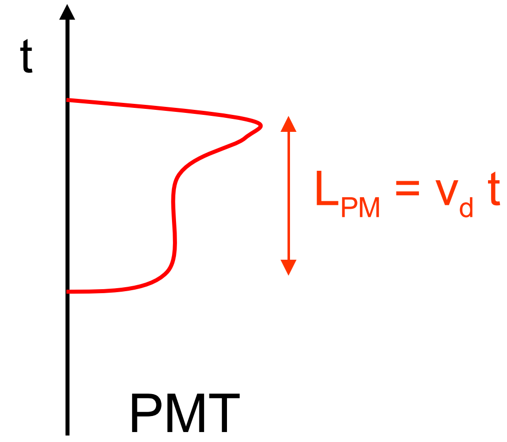
National Superconducting Cyclotron Laboratory
- T. Ginter
- A. Stolz

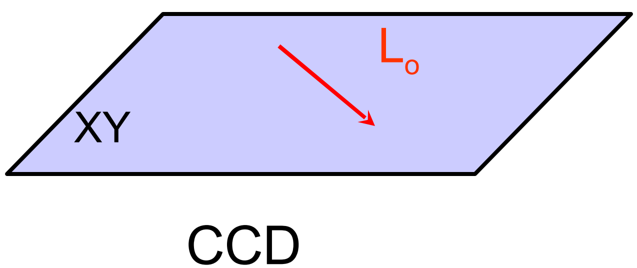
University of Tennessee
- C. Bingham
- I. Darby
- R. Grzywacz
- S. Liddick
- M. Rajabali

Dubna, Joint Institute for Nuclear Reasearch
- A. Fomichev
- M. Golovkov
- A. Rodin
- S. Stepantsov
- R. Slepnev
- G. M. Ter-Akopian
- R. Wolski

Event reconstruction







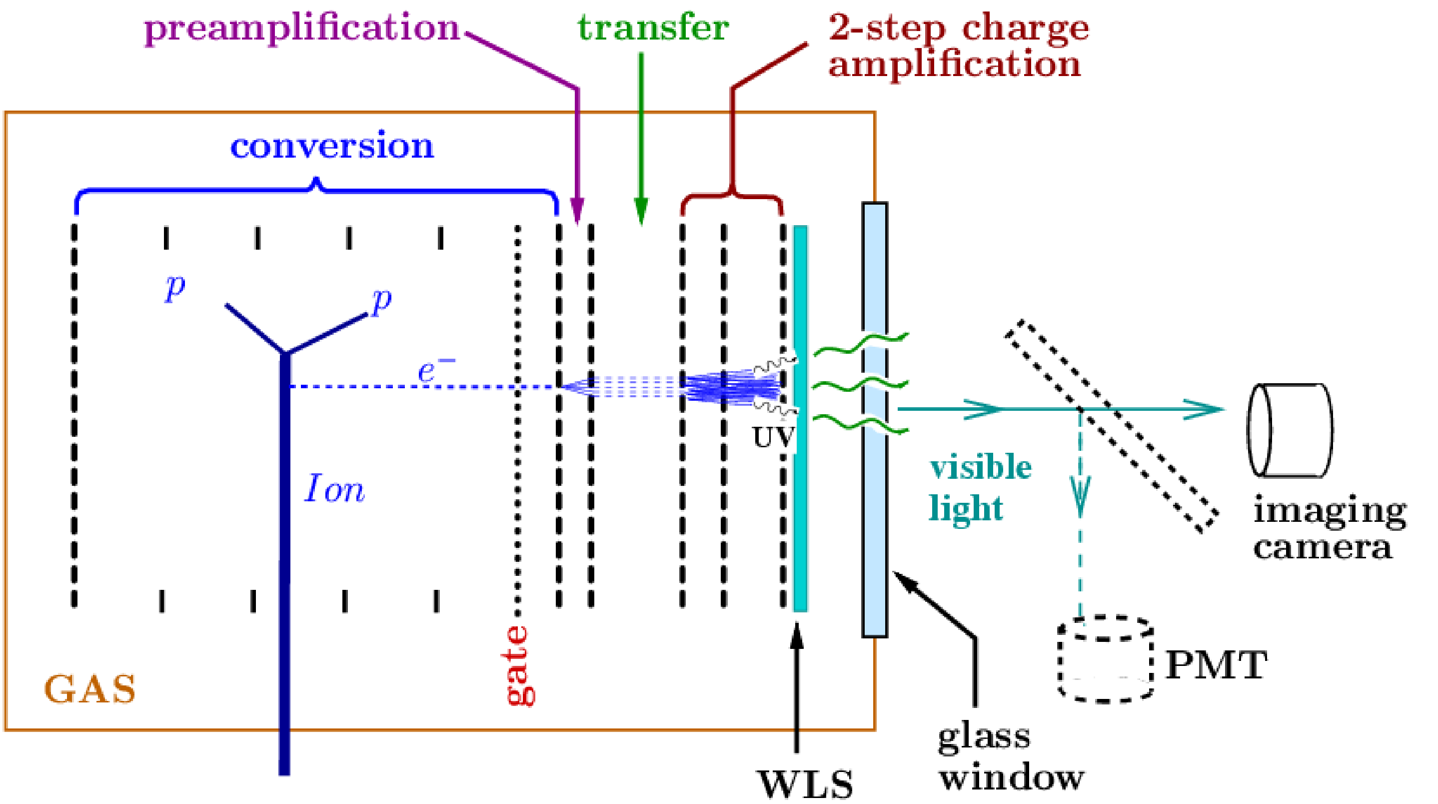
Track coordinates: (r, Θ, φ)

$L_o = r \cos\Theta$
$L_{PM} = r \sin\Theta$

$r^2 = L_o^2 + L_{PM}^2$
$\Theta = \arctan(L_o/L_{PM})$

K. Miernik

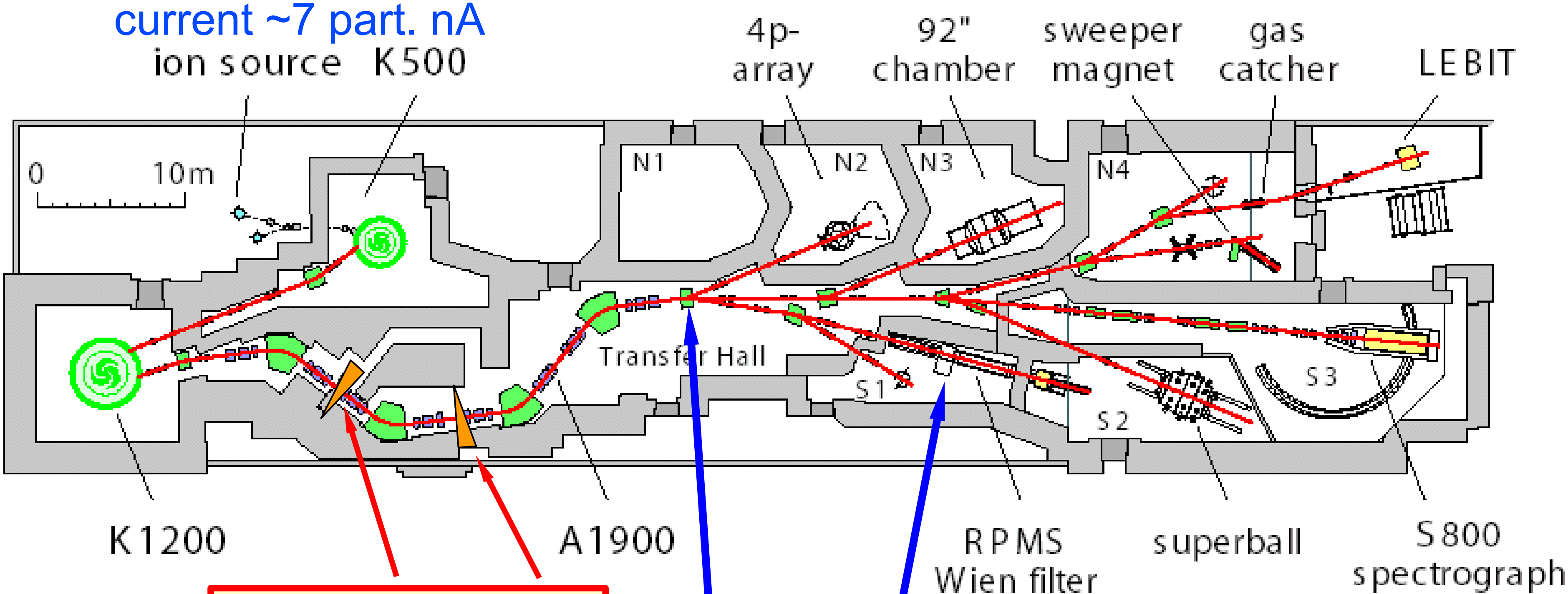
Principle of operation of the Optical Time Projection Chamber.



M. Pfutzner at al. Warsaw University

Experiment Layout

Beam: ^{58}Ni @ 160 A•MeV
current ~7 part. nA



Wedges at I1 and/or I2

Final focal plane I4 of A1900

S1 vault

Detection system : ΔE + TOF particle ID