Nuclear Structure II
experimental

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Sunday

Monday

The neutron dripline

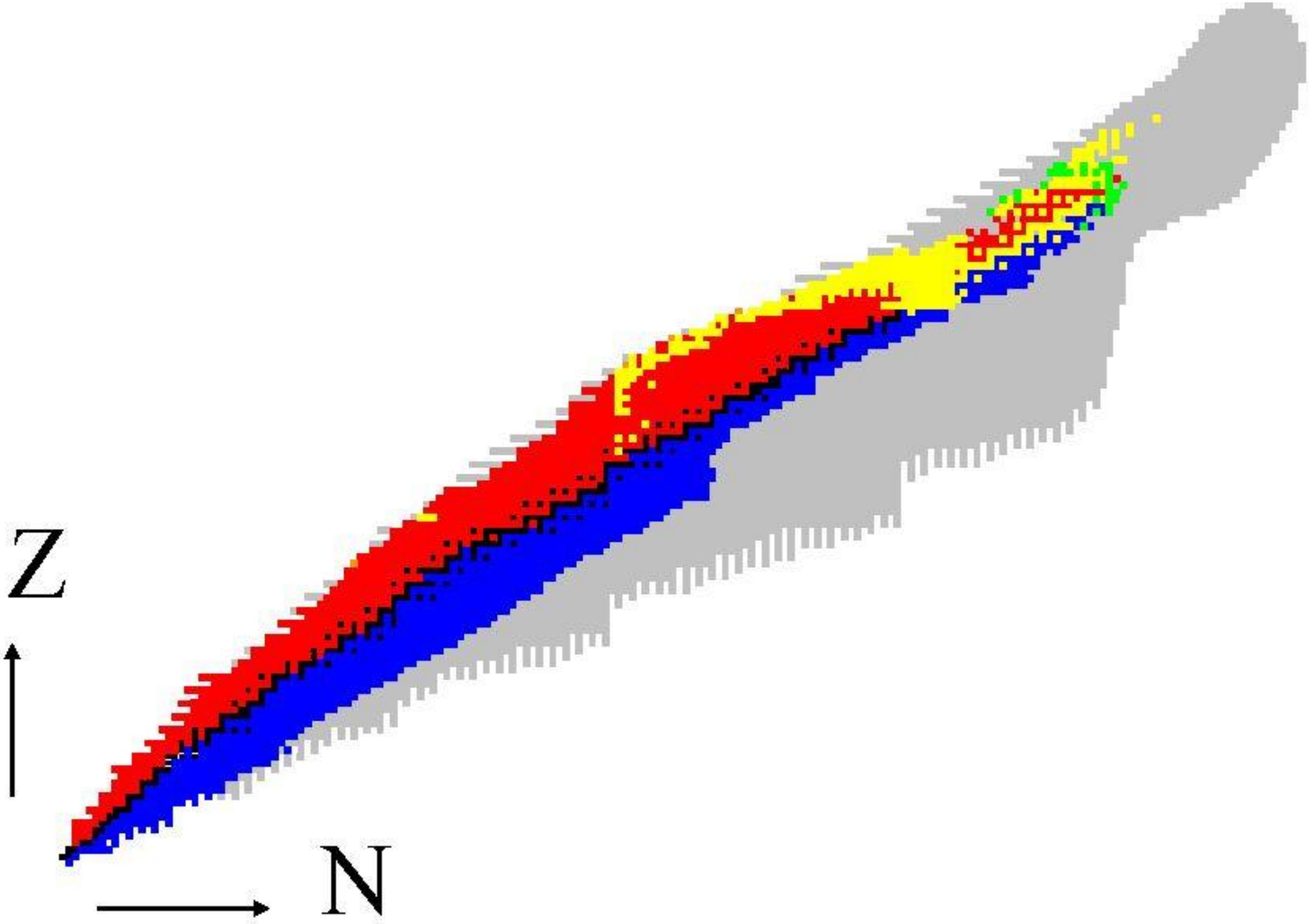
Physics at and beyond the proton dripline

Nuclear ground states – Half-life measurements

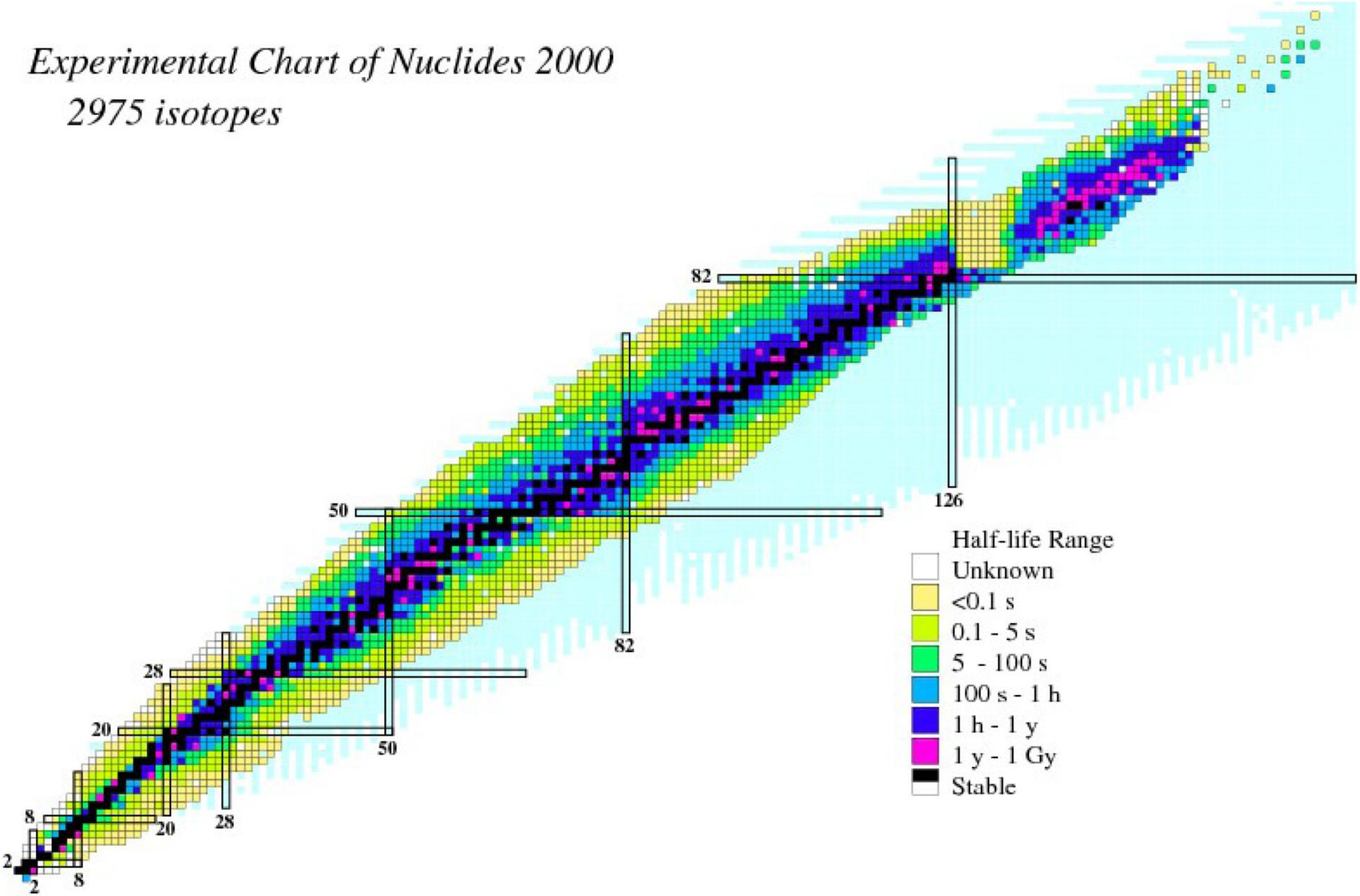
Thursday

Friday

Exotic nuclei – decays

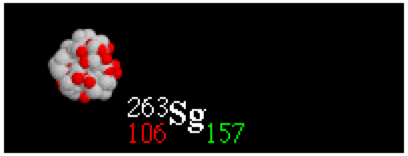


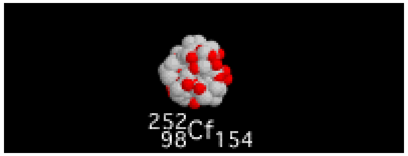
Exotic nuclei - halflives



4 basic decay modes

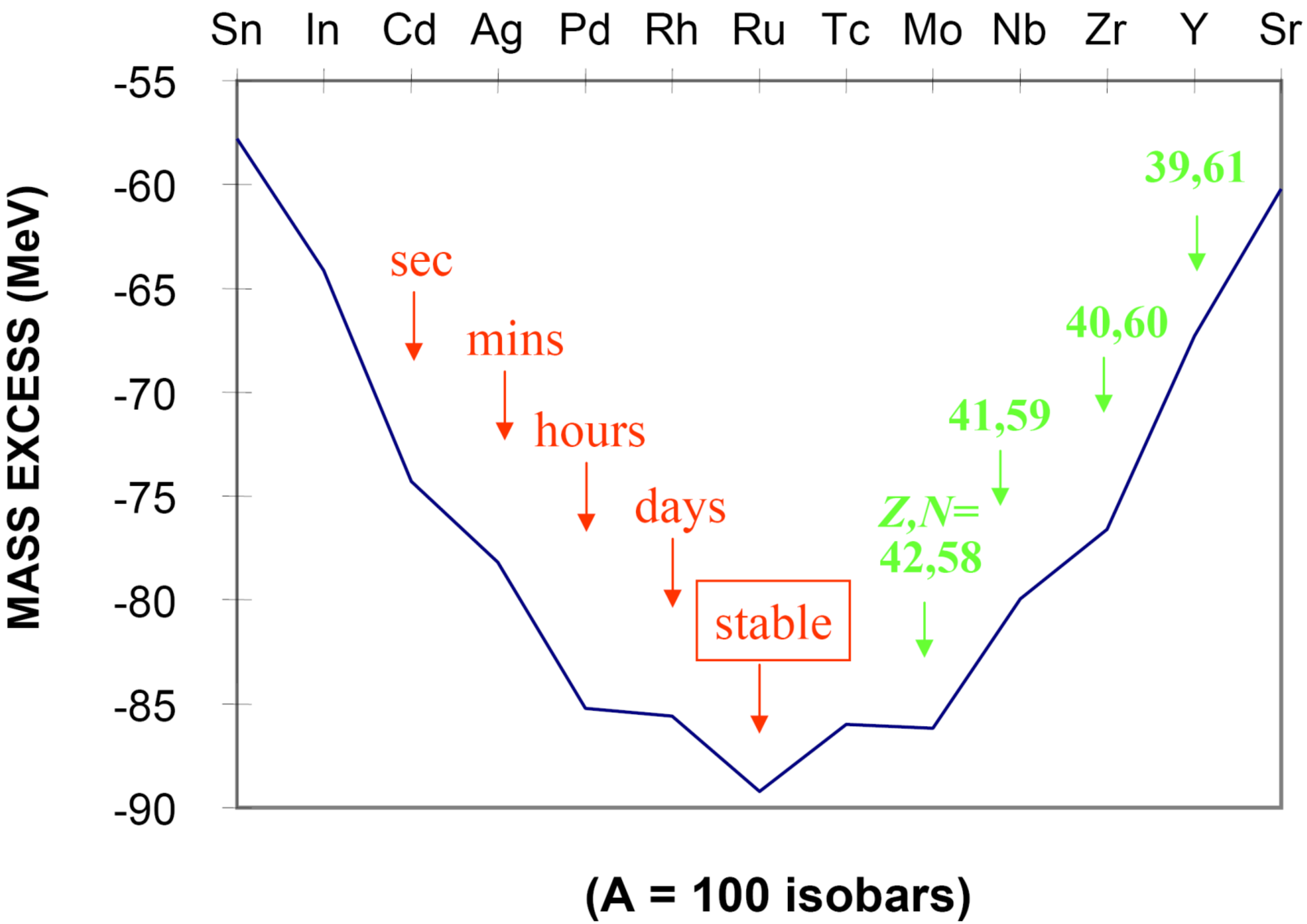
- Nuclei decay via 4 basic modes:
  - Alpha decay (Z-2, N-2)
  - Beta(-) decay (Z+1, N-1)
  - Beta(+) decay (Z-1, N+1)
  - Fission into two large fragments and a few neutrons





There is also one-proton and two-proton radioactivity

Decays toward stability



Location of the driplines

Experimental task: How to find a needle in a haystack

How many neutrons can a proton bind?

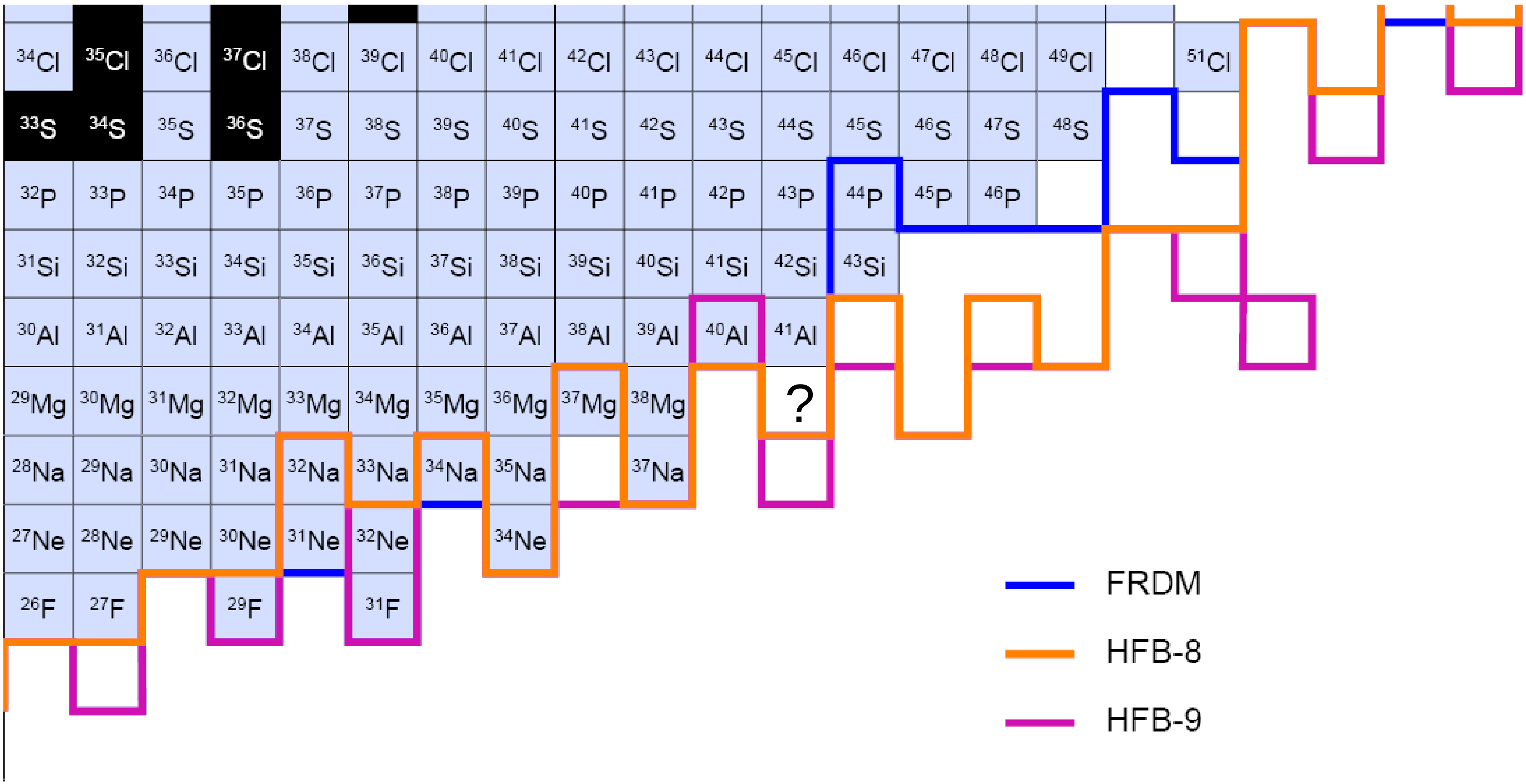
The limit of nuclear existence is characterized by the nucleon driplines

- B. Jonson: "The driplines are the limits of the nuclear landscape where additional protons or neutrons can no longer be kept in the nucleus - they literally drip out.“

- P. G. Hansen & J. A. Tostevin: "(the dripline is) where the nucleon separation energy goes to zero."

Where is the neutron dripline?

Predictive power, anybody?

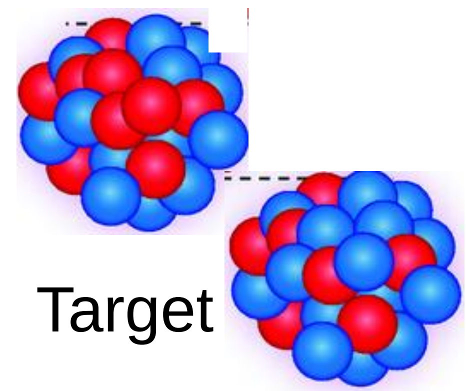


Dripline history and a plan …

^{36}Ca	^{37}Ca	^{38}Ca	^{39}Ca	^{40}Ca	^{41}Ca	^{42}Ca	^{43}Ca	^{44}Ca	^{45}Ca	^{46}Ca	^{47}Ca	^{48}Ca
^{35}K	^{36}K	^{37}K	^{38}K	^{39}K	^{40}K	^{41}K	^{42}K	^{43}K	^{44}K	^{45}K	^{46}K	^{47}K
^{34}Ar	^{35}Ar	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	^{41}Ar	^{42}Ar	^{43}Ar	^{44}Ar	^{45}Ar	^{46}Ar
^{33}Cl	^{34}Cl	^{35}Cl	^{36}Cl	^{37}Cl	^{38}Cl	^{39}Cl	^{40}Cl	^{41}Cl	^{42}Cl	^{43}Cl	^{44}Cl	^{45}Cl
^{32}S	^{33}S	^{34}S	^{35}S	^{36}S	^{37}S	^{38}S	^{39}S	^{40}S	^{41}S	^{42}S	^{43}S	^{44}S
^{31}P	^{32}P	^{33}P	^{34}P	^{35}P	^{36}P	^{37}P	^{38}P	^{39}P	^{40}P	^{41}P	^{42}P	^{43}P
^{30}Si	^{31}Si	^{32}Si	^{33}Si	^{34}Si	^{35}Si	^{36}Si	^{37}Si	^{38}Si	^{39}Si	^{40}Si	^{41}Si	^{42}Si
^{29}Al	^{30}Al	^{31}Al	^{32}Al	^{33}Al	^{34}Al	^{35}Al	^{36}Al	^{37}Al	^{38}Al	^{39}Al	^{40}Al	^{41}Al
^{28}Mg	^{29}Mg	^{30}Mg	^{31}Mg	^{32}Mg	^{33}Mg	^{34}Mg	^{35}Mg	^{36}Mg	^{37}Mg	^{38}Mg		**^{40}Mg**
^{27}Na	^{28}Na	^{29}Na	^{30}Na	^{31}Na	^{32}Na	^{33}Na	^{34}Na	^{35}Na		^{37}Na		
^{26}Ne	^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne	^{31}Ne	^{32}Ne		^{34}Ne				
^{25}F	^{26}F	^{27}F		^{29}F		^{31}F						
^{24}O		^{26}O		^{28}O								

1990 (^{26}O) **1997** (^{28}O) **1999** (^{31}F) **2002** (^{34}Ne) **2002** (^{37}Na)

^{48}Ca (Z=20, N=28)

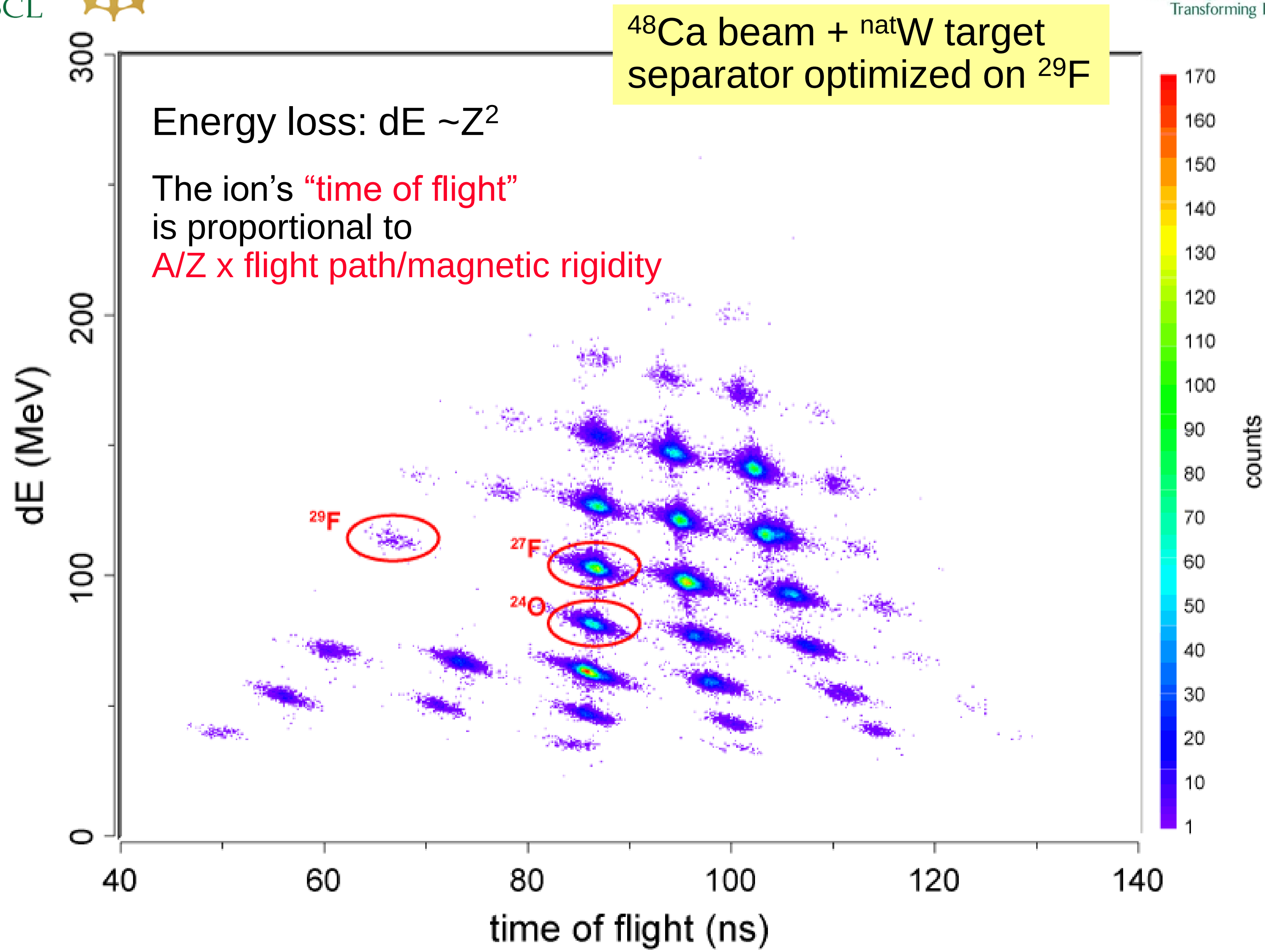


Target

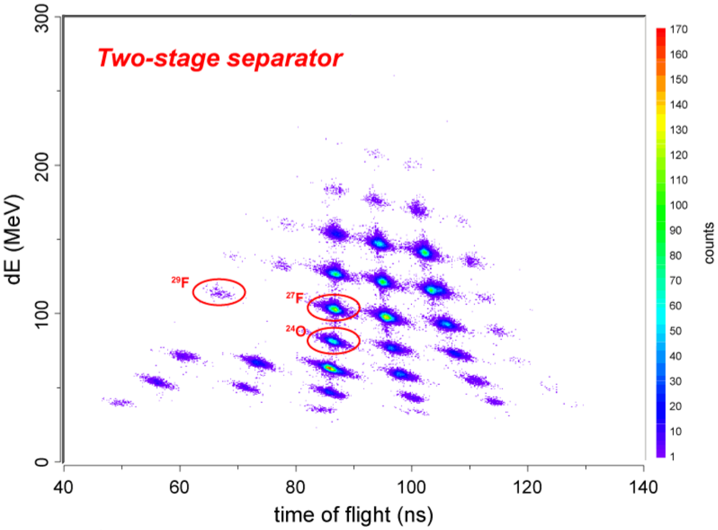
Production of ^{40}Mg from ^{48}Ca: Net loss of 8 protons with no neutrons removed!

1990: Guillemaud-Mueller et al., Z. Phys. A 332, 189
1997: Tarasov et al., Phys. Lett. B 409, 64
1999: Sakurai et al., Phys. Lett. B 448, 180
2002: Notani et al., Phys. Lett. B 542, 49
Lukyanov et al., J. Phys. G 28, L41

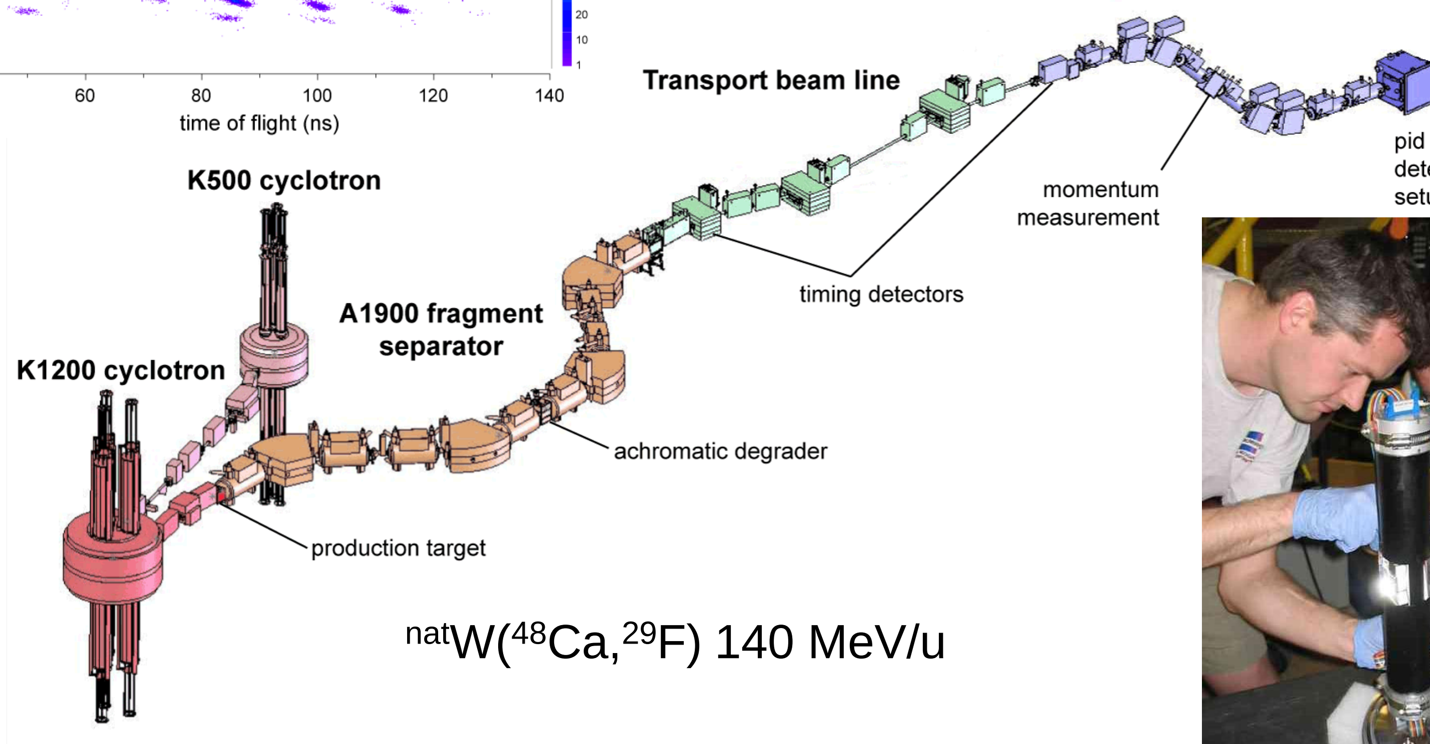
Proof of existence? Detect and identify it!



A long way …



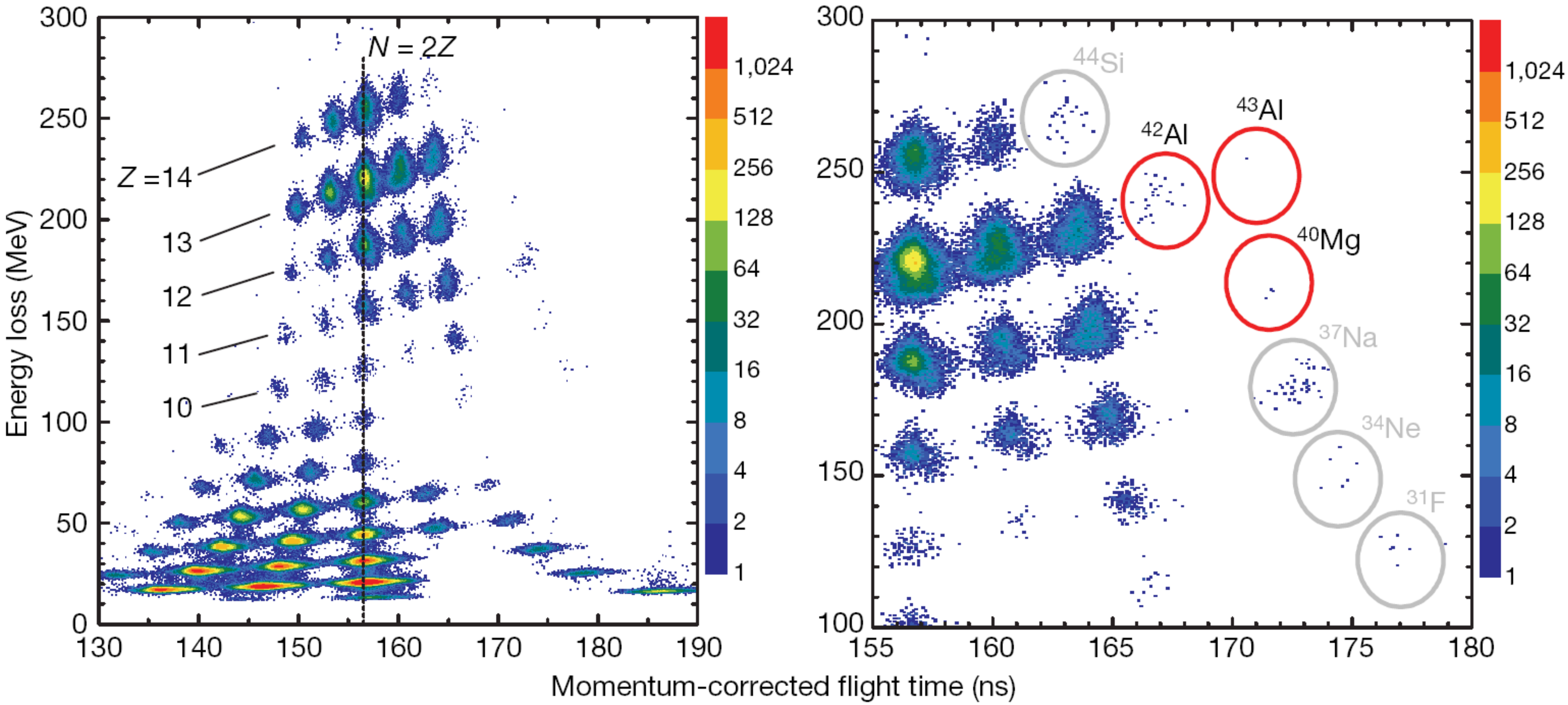
- Two test experiments at the end of the fragment separator
- During the tests: Production cross sections of neutron-rich isotopes and discovered ^{44}Si along the way
- Implemented the concept of a two-stage separator to discriminate against low-Z events
- … and finally ran the search for ^{40}Mg in April 2007

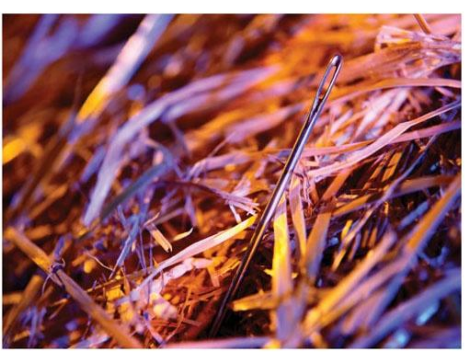


$^{nat}W(^{48}Ca,^{29}F)$ 140 MeV/u

^{40}Mg and more!

nature T. Baumann *et al*., Nature 449, 1022 (2007)





Data taking: 7.6 days at 5 x10^{11} particles/second
3 events of ^{40}Mg
23 events of ^{42}Al
1 event ^{43}Al

The existence of ^{42,43}Al …

nature T. Baumann *et al*., Nature 449, 1022 (2007)

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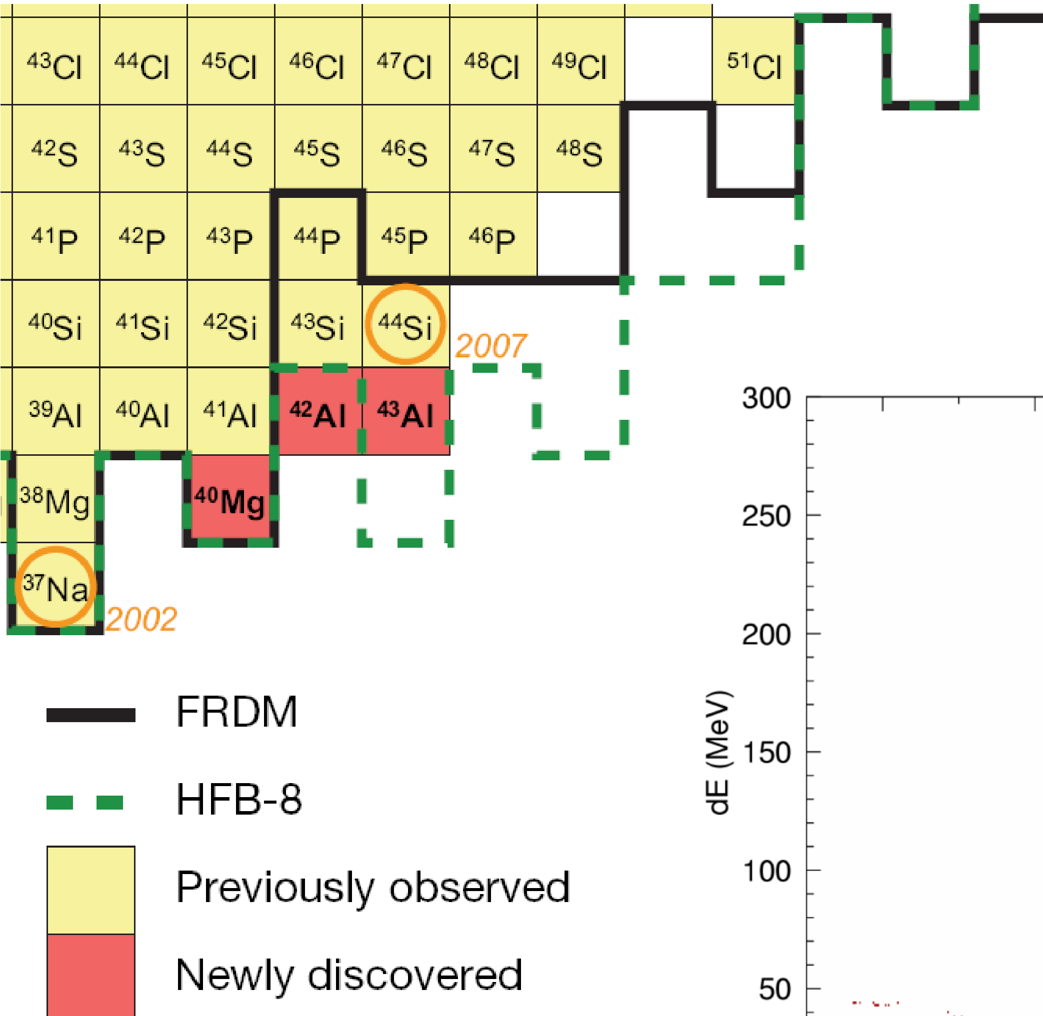
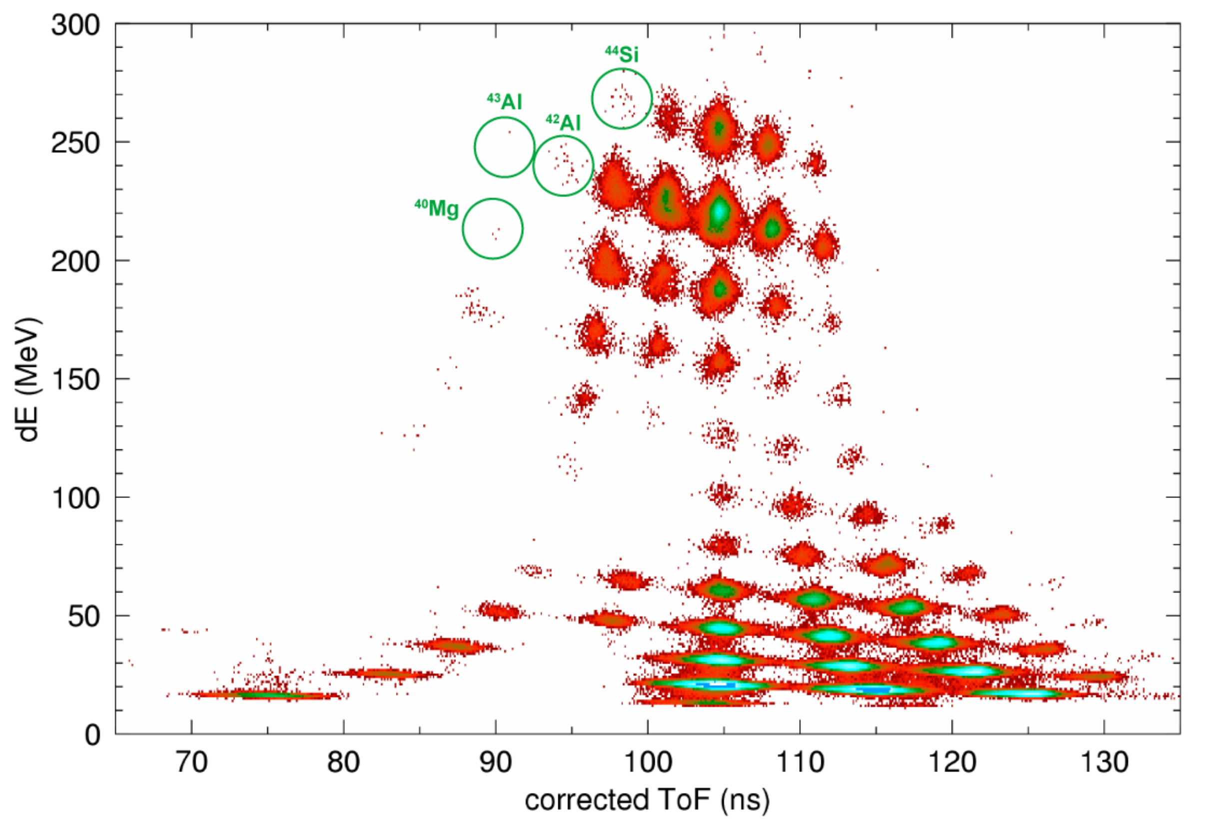
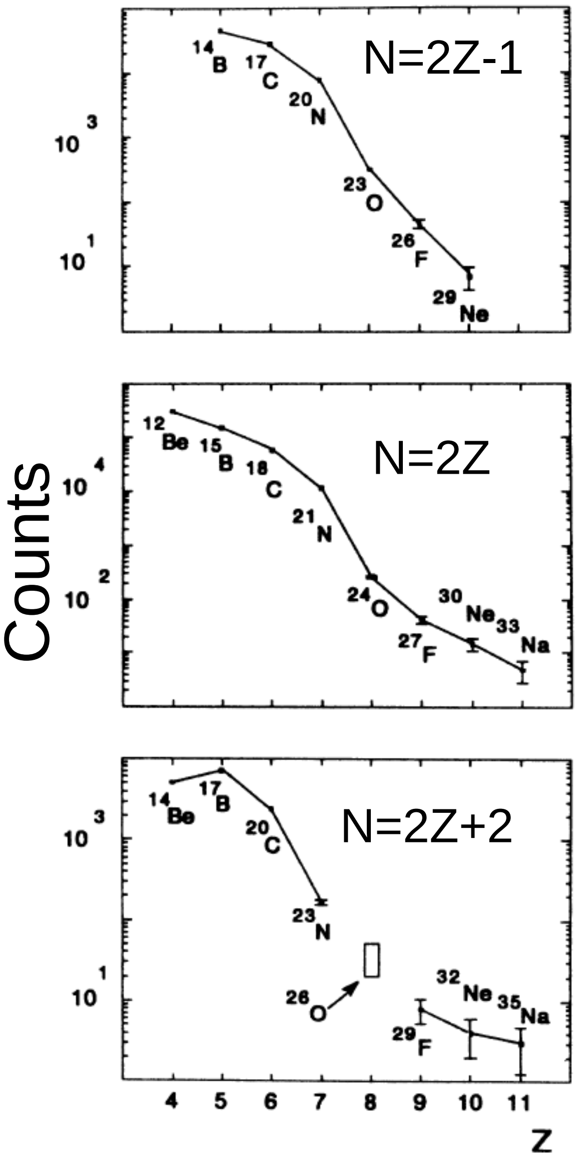


The existence of ^{42,43}Al indicates that the neutron dripline might be much further out than predicted by most of the present theoretical models, certainly out of reach at present generation facilities.



Proof of non-existence: ^{26}O and ^{28}O

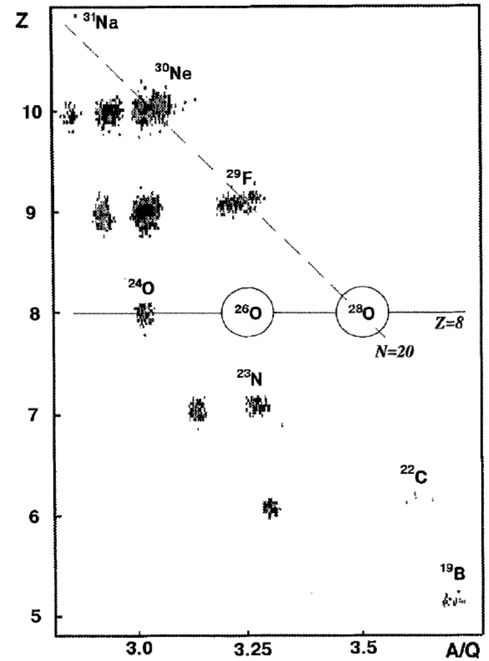
Guillemaud-Mueller et al., PRC 41, 937 (1990)



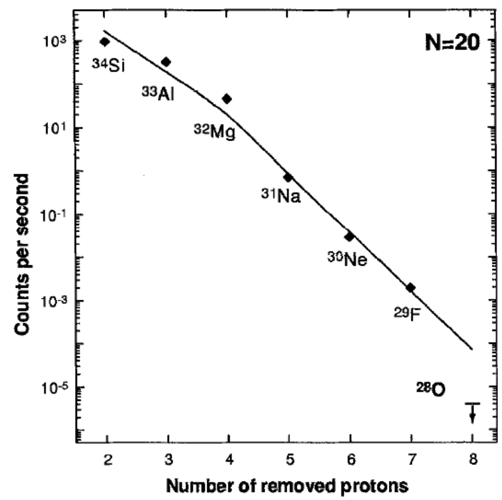
^{48}Ca on Ta
at 44 MeV/u
(GANIL)

Report absence of ^{26}O in N=2Z+2 systematics

Tarasov et al., PLB 409, 64 (1997)



^{36}S on Ta
at 78 MeV/u
(GANIL)



Report absence of ^{28}O in the systematics of produced N=20 isotones

Decay modes at the proton drip line

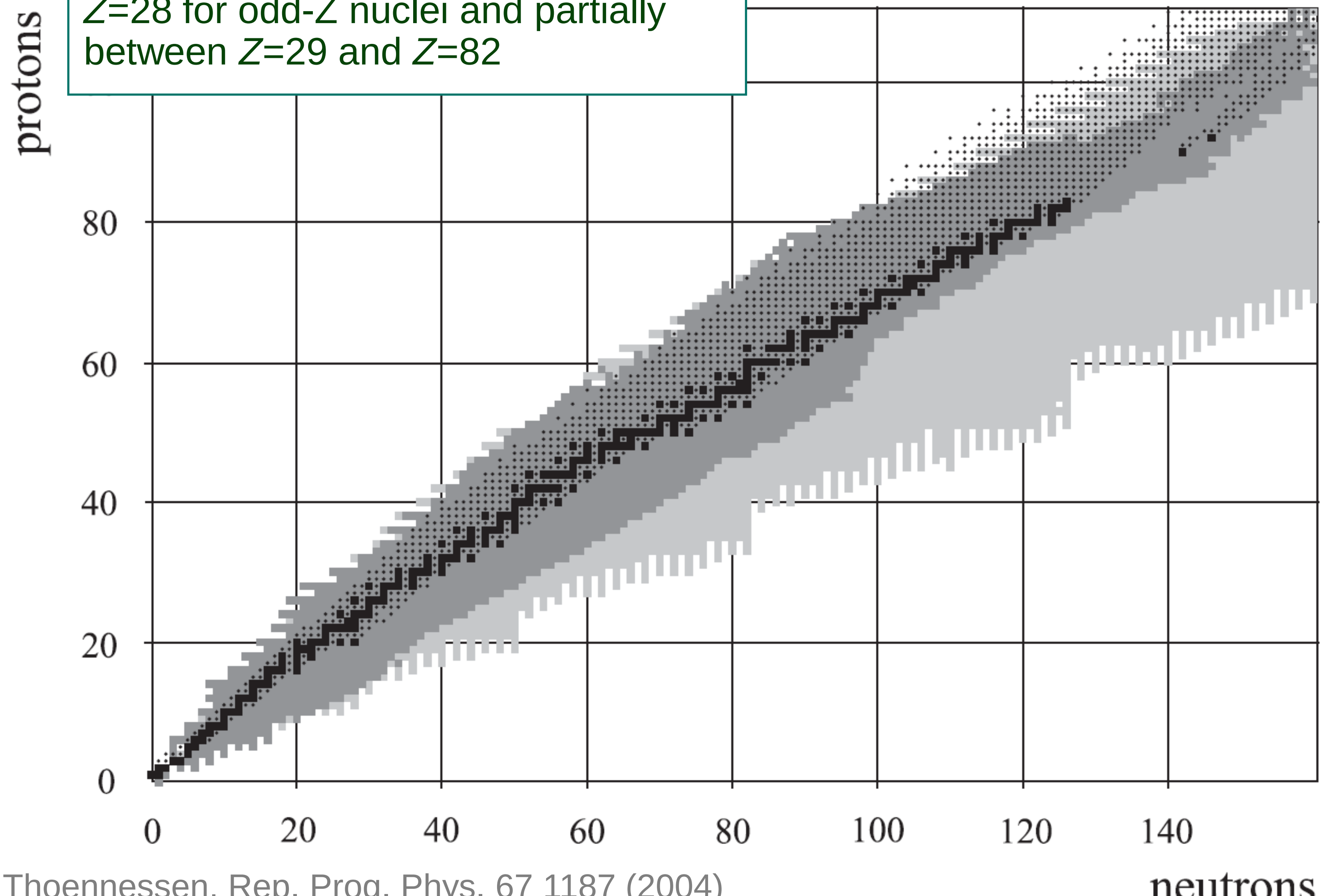
One-proton radioactivity – Direct proton emission from ground states or isomeric excited states (heaviest proton emitter ^{185}Bi (isomeric state), the heaviest gs emitter: ^{177}Tl

β-delayed charged particle emission (βp, β2p, for heavier nuclei βα, βαp) – Half-lives are dominated by β-decay, proton emission proceeds at half-lives of femto seconds or shorter → not considered as "proton radioactivity"

Two-proton radioactivity – Two-proton emission from even-Z nuclei, for which, due to the pairing force, one proton emission is energetically forbidden, while two-proton emission is allowed (so far, ^{45}Fe, ^{54}Zn, indications in ^{48}Ni)

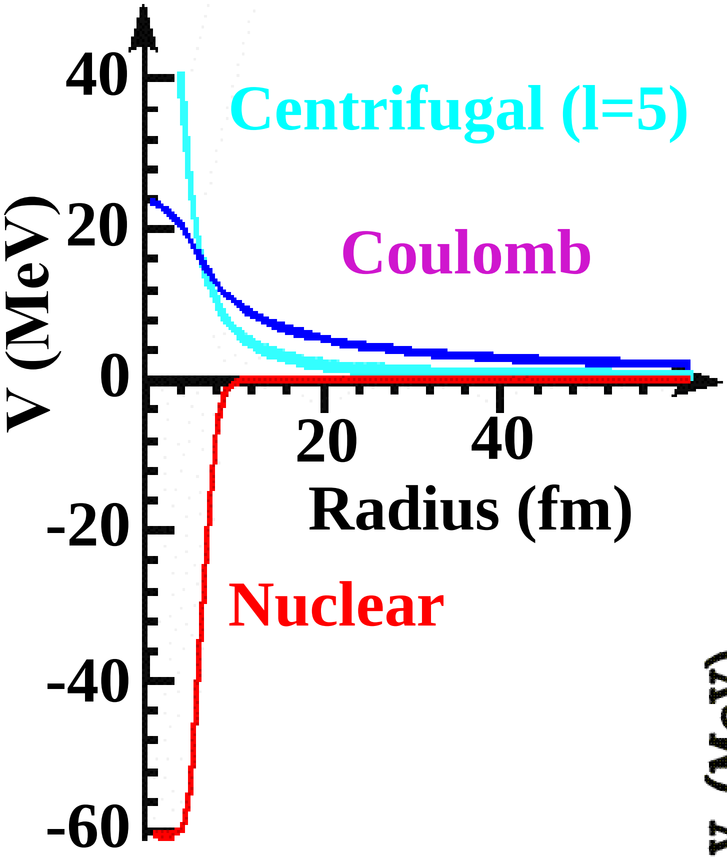
Where is the proton dripline?

Proton dripline is established up to *Z*=28 for odd-Z nuclei and partially between *Z*=29 and *Z*=82



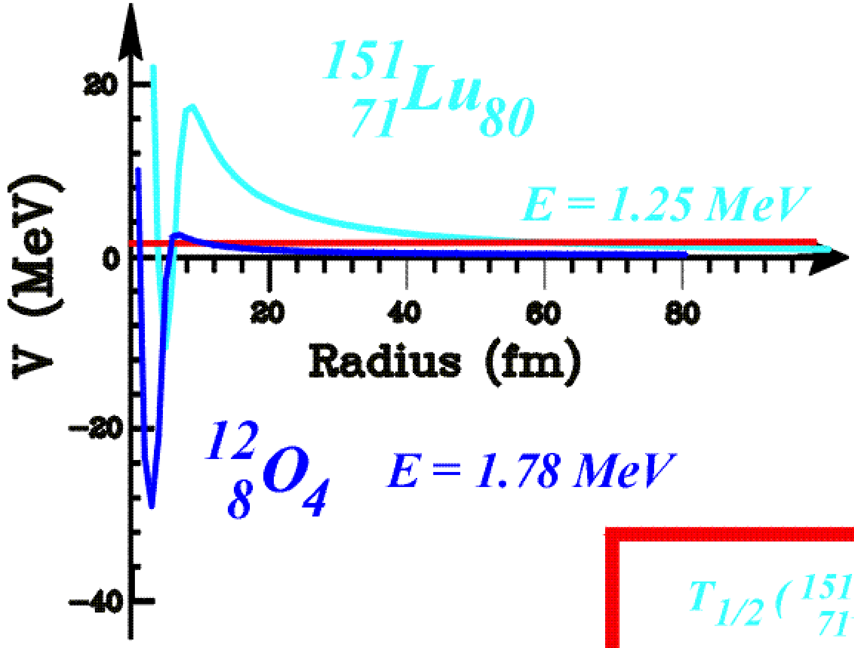
M. Thoennessen, Rep. Prog. Phys. 67 1187 (2004)

Proton radioactivity/emission



Light proton emitters:

- (Very) short lifetimes due to small Coulomb and no or very small angular momentum barrier (l=0,1,2)
- Produced in transfer reactions or fragmentation
- Identify by complete kinematic reconstruction in flight

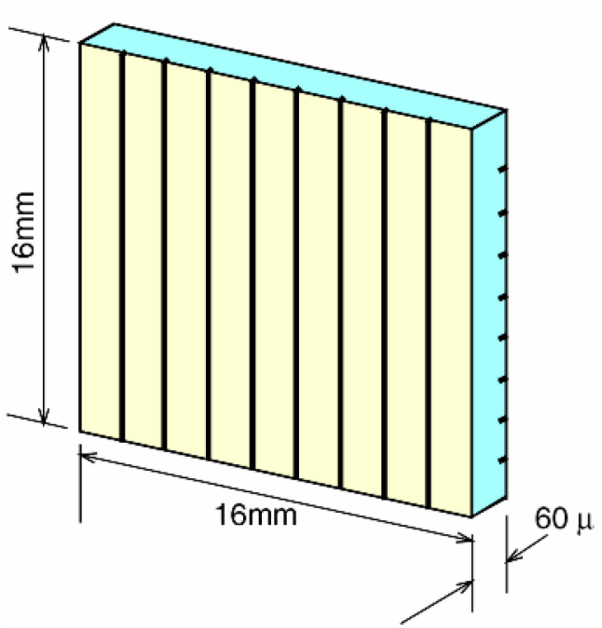


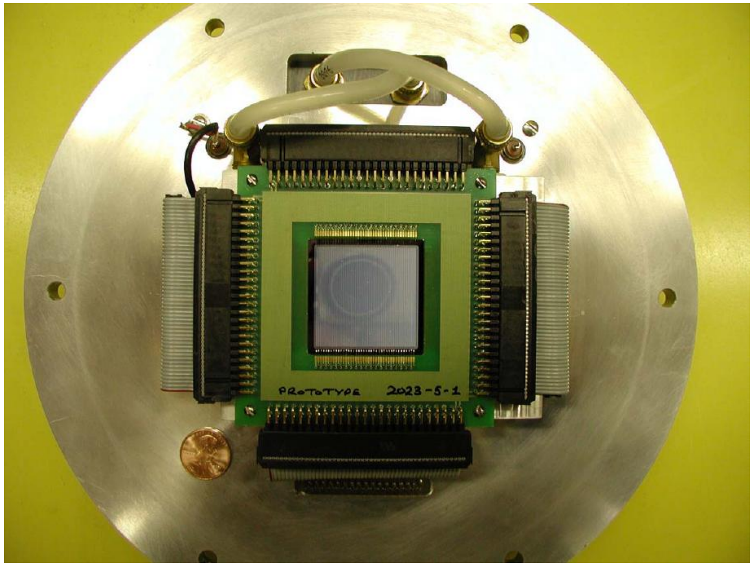
$T_{1/2}(^{151}_{71}Lu_{80}) = 81ms$

$T_{1/2}(^{12}_{8}O_{4}) \sim 10^{-21} s$

Heavy proton emitters

- Long lifetimes due to Coulomb and angular momentum barrier
- Typically produced in fusion evaporation reactions or fragmentation
- Separate and subsequently stop in a detector for identification
- Use segmented silicon strip detectors for a delayed decay (e.g., DSSD)

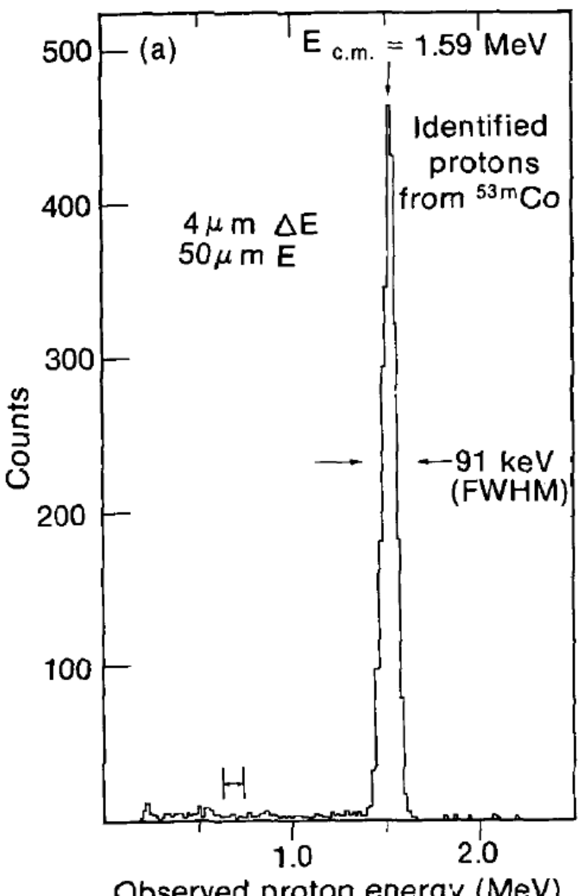


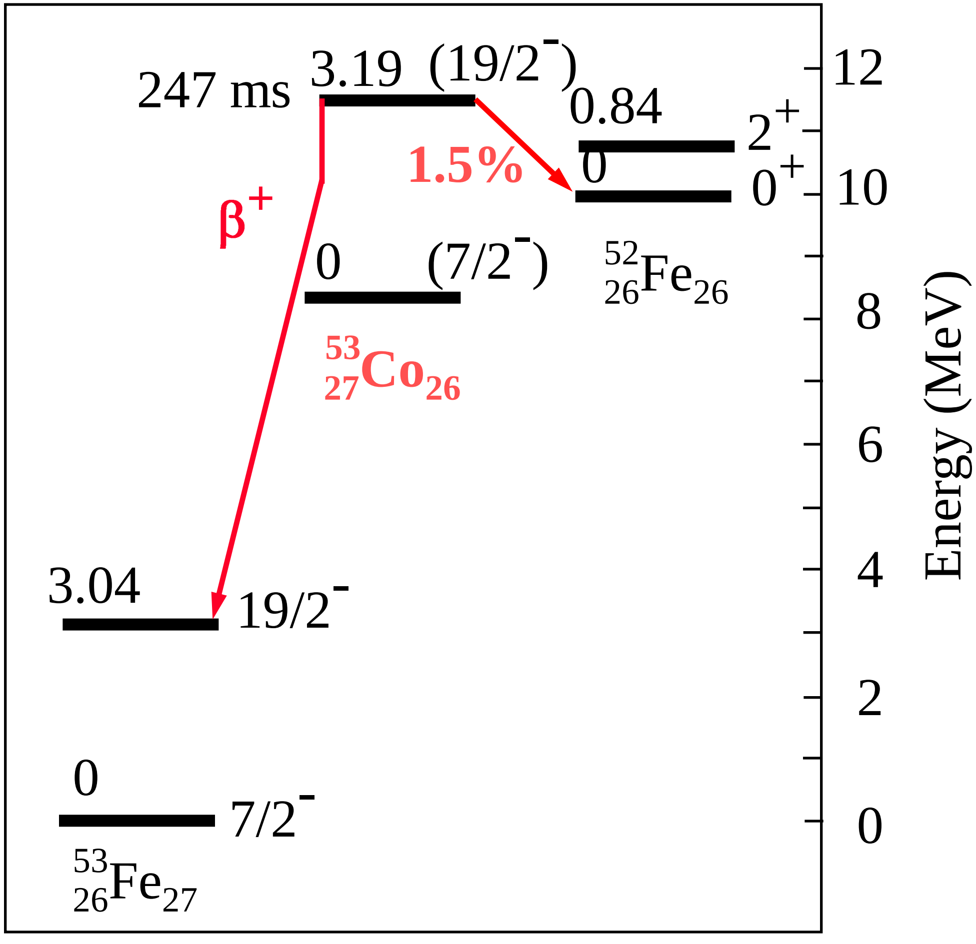


Adapted from C. N. Davids

First Proton Radioactivity
1970

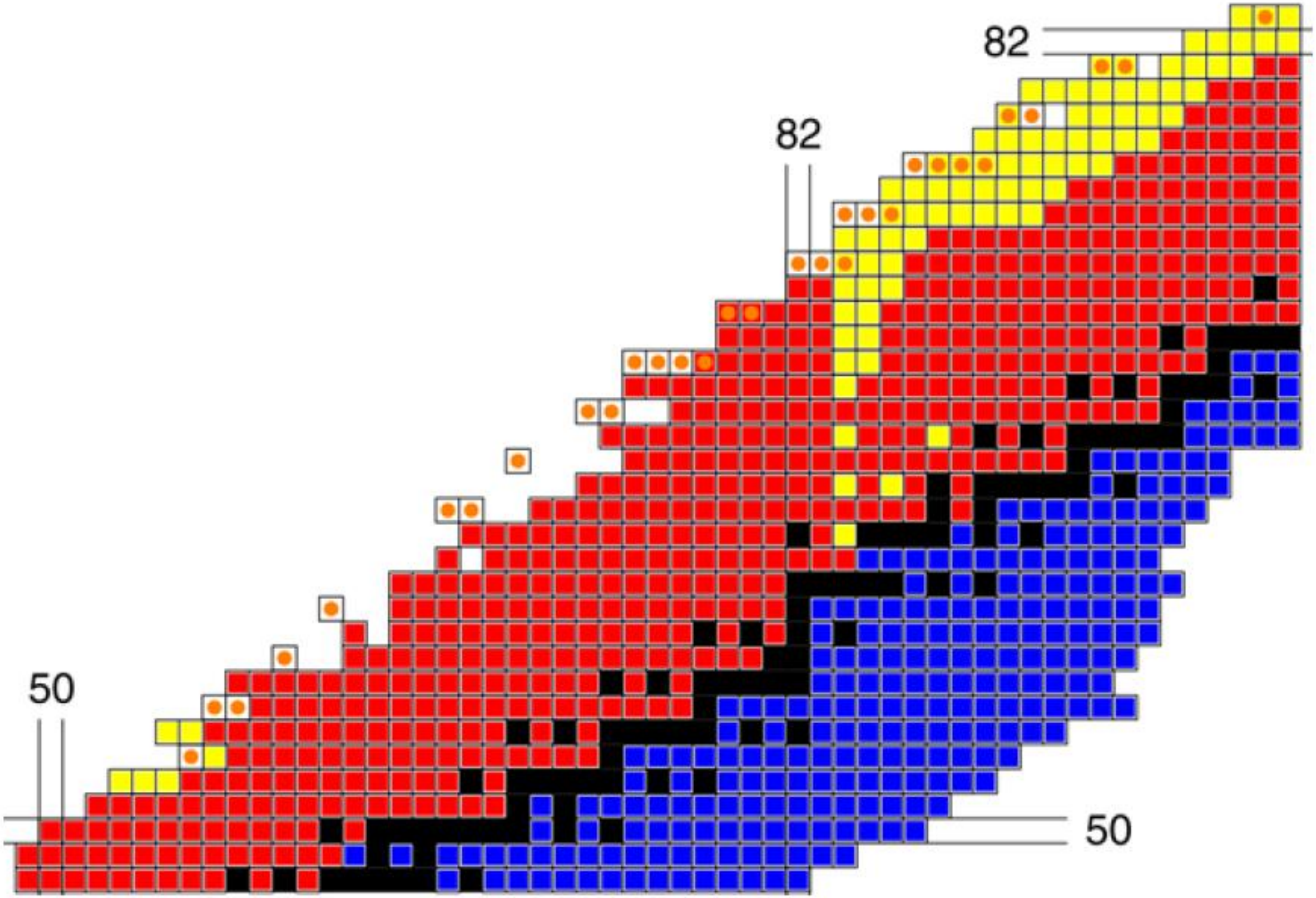
^{53}Co produced in ^{54}Fe(p,2n)





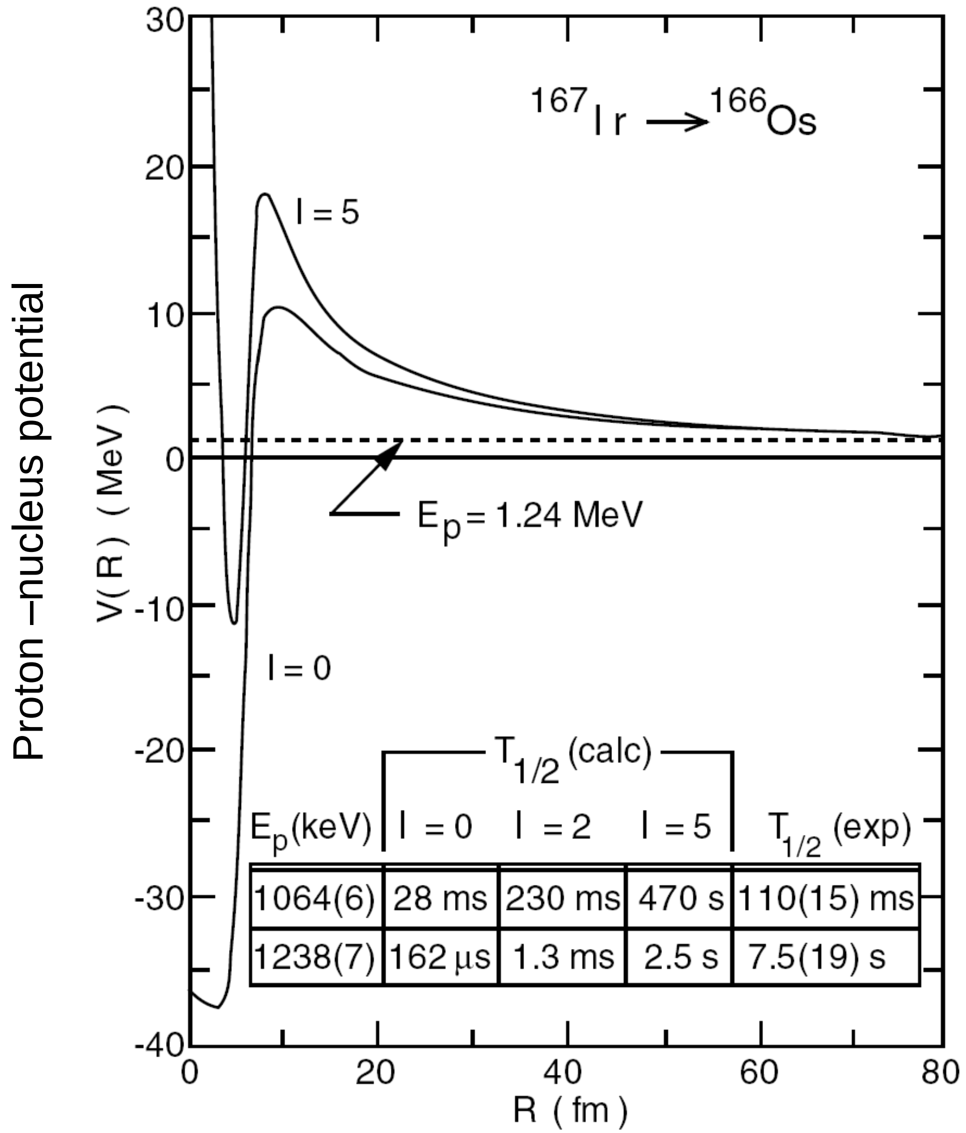
J. Cerny and J. C. Hardy, Annu. Rev. Nucl. Part. Sci. 27, 333 (1977)

Proton emitters between Z=53 and 83



B. Blank and M.J.G. Borge, PPNP 60, 403 (2008)

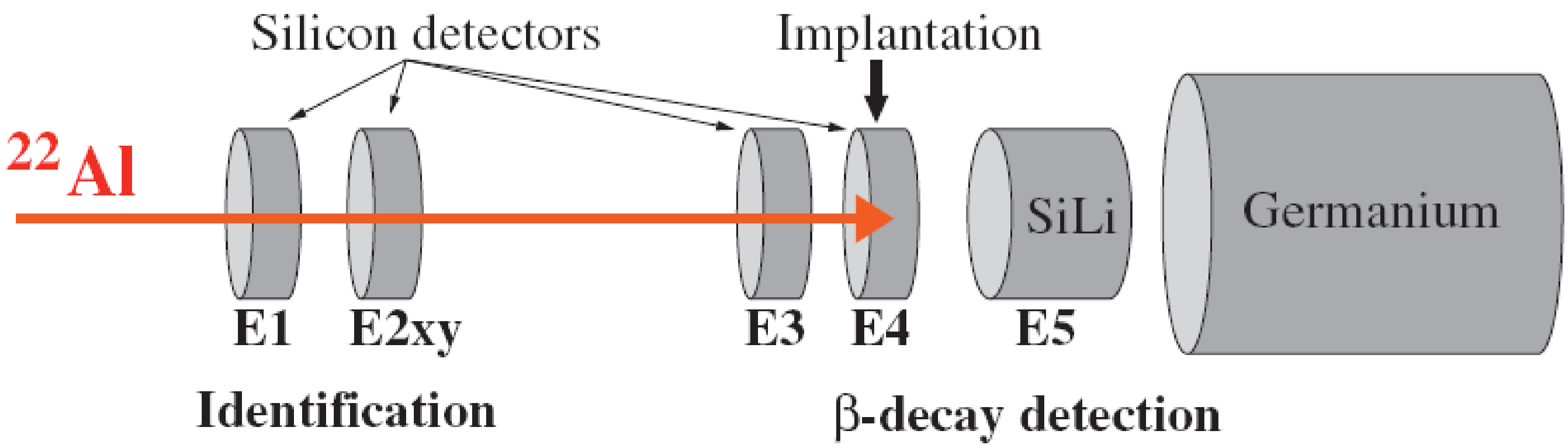
Half-life dependence on angular momentum and energy



E_p(keV)	$T_{1/2}$(calc) l = 0	$T_{1/2}$(calc) l = 2	$T_{1/2}$(calc) l = 5	$T_{1/2}$ (exp)
1064(6)	28 ms	230 ms	470 s	110(15) ms
1238(7)	162 μs	1.3 ms	2.5 s	7.5(19) s

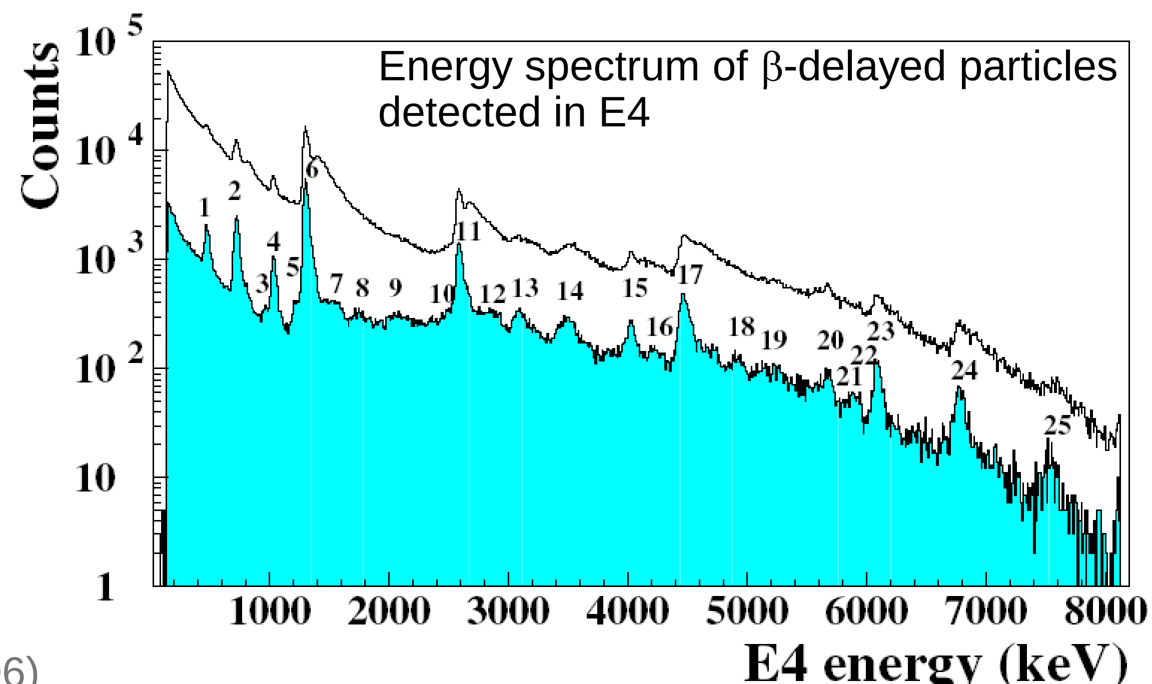
P. J. Woods and C. N. Davids, ARNPS 47, 541 (1997)

β-delayed proton emitters
The decay of ^{22}Al



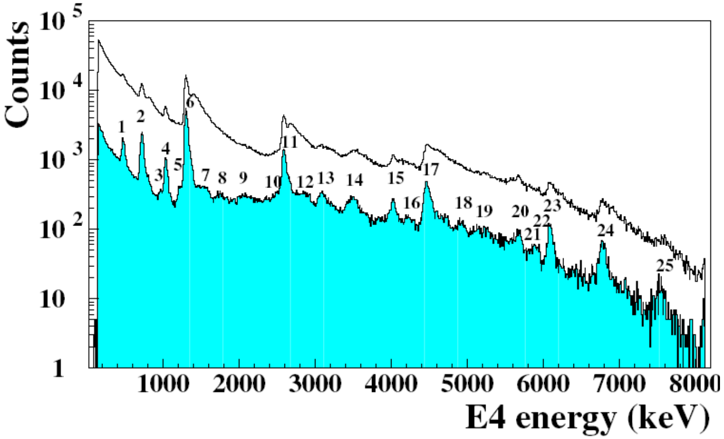
^{22}Al produced in the fragmentation of 95 MeV/u ^{36}Ar at GANIL(LISE3)

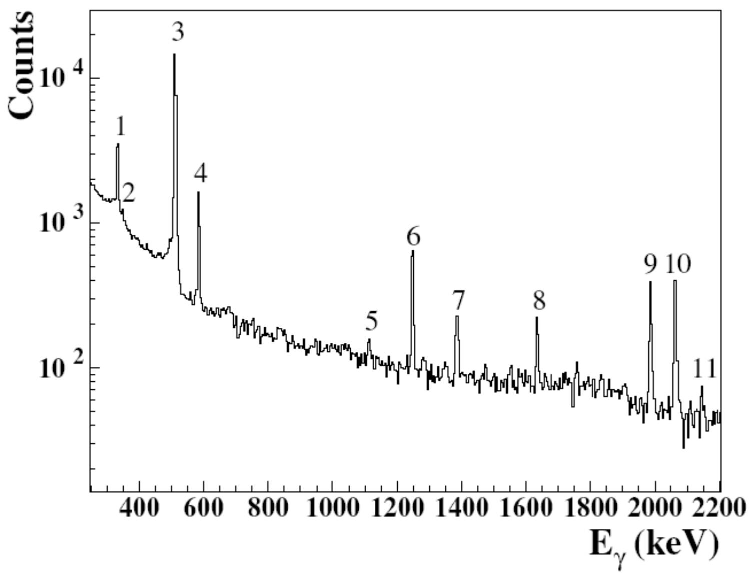
For example …
23: β2p to ^{20}Ne gs
15: βα to ^{18}Ne 2^+_1

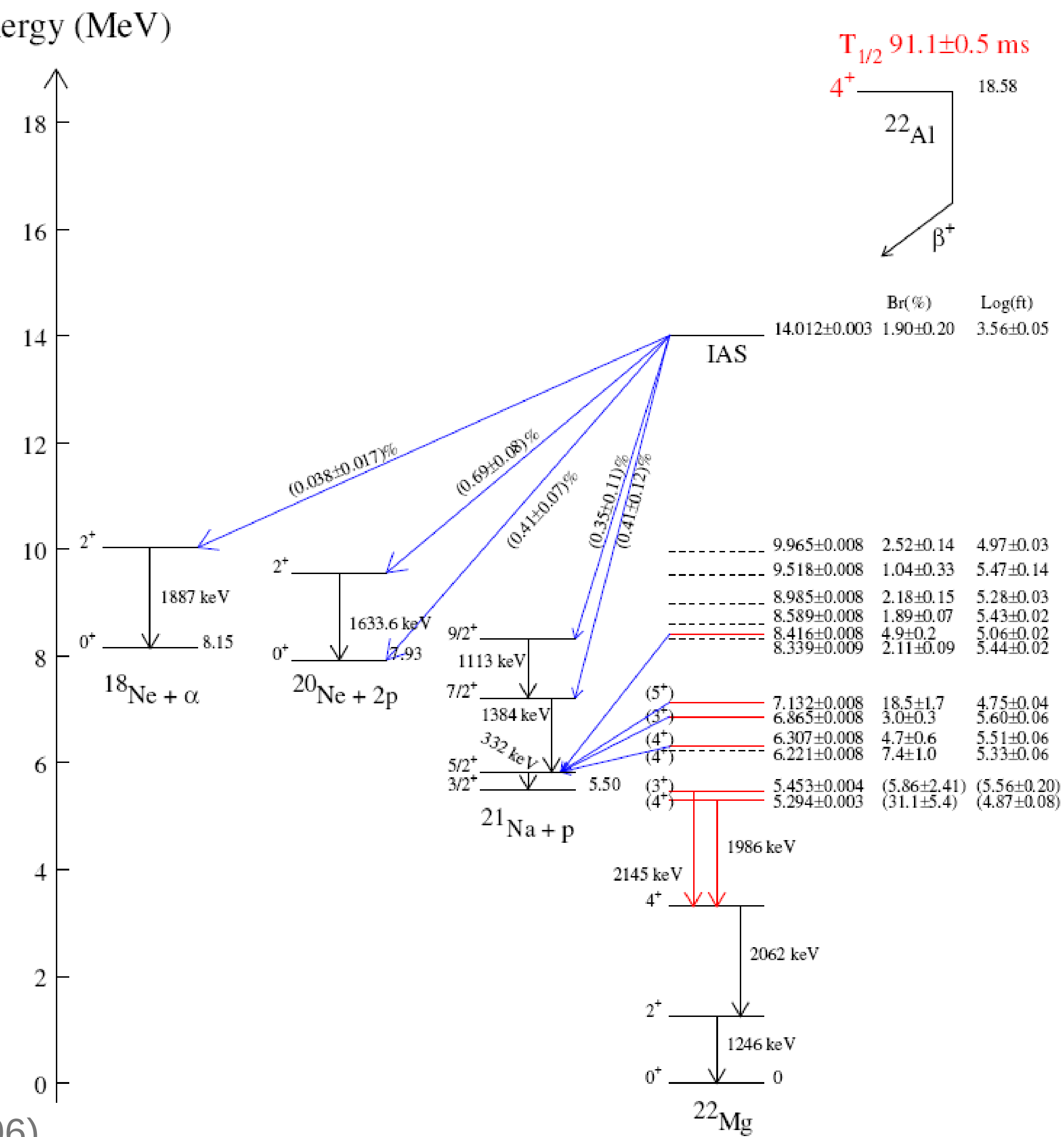


N. L. Achouri et al., EPJ A 27, 287 (2006)

β-delayed proton emitters
The decay of ^{22}Al





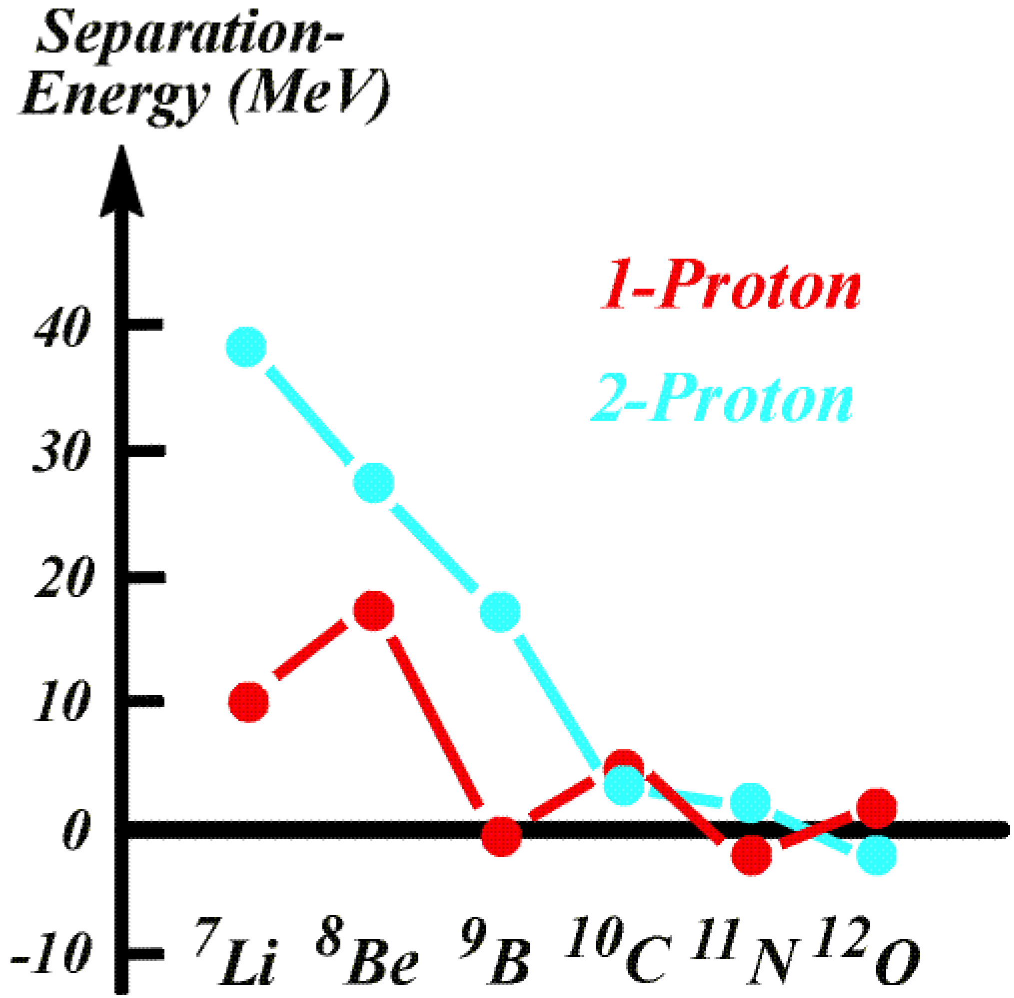


N. L. Achouri et al., EPJ A 27, 287 (2006)

Two-proton radioactivity

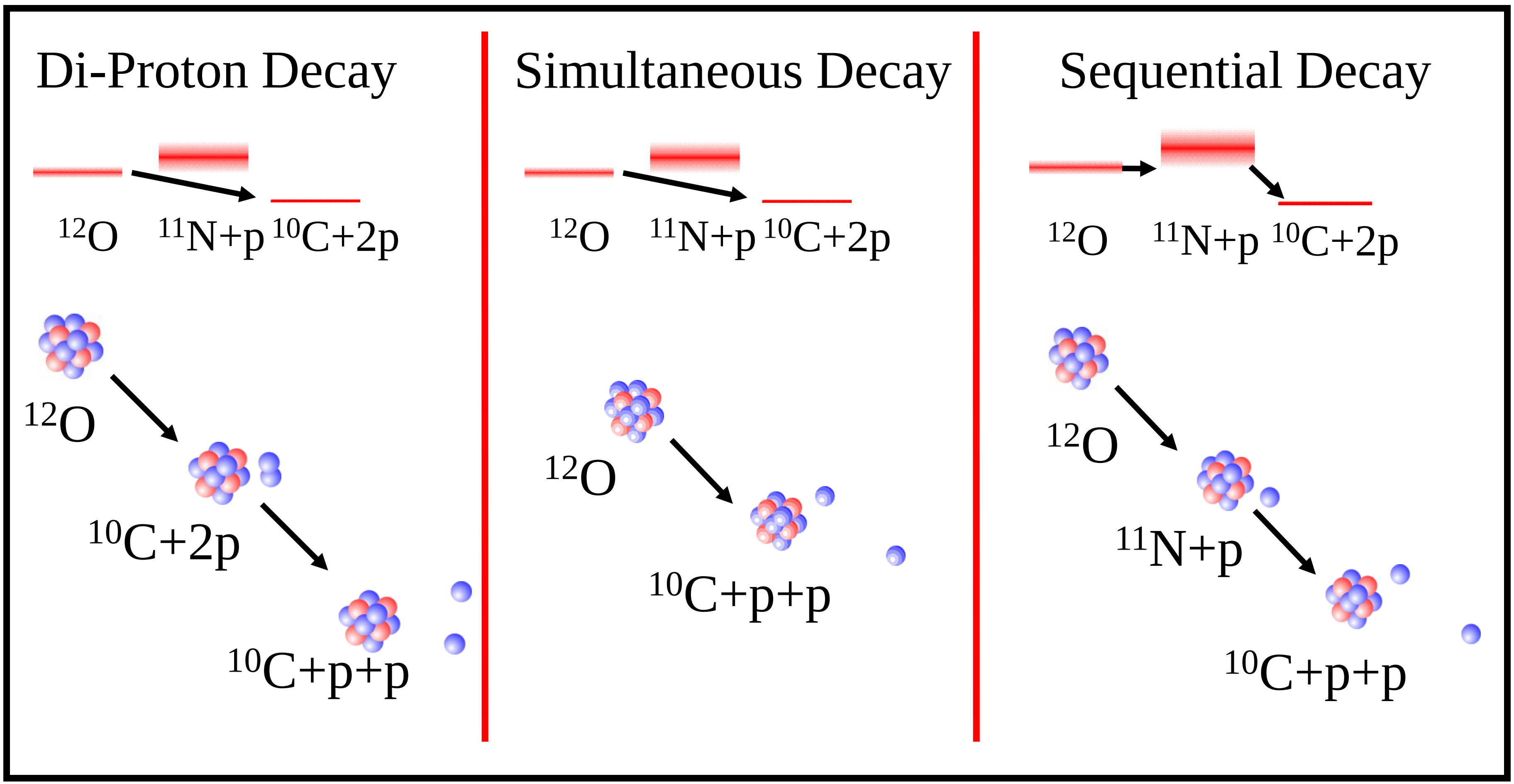
- Predicted by Goldanskii in 1960
- Discovered recently in ^{45}Fe, ^{54}Zn and possibly ^{48}Ni
- Implantation/Decay (Long lifetimes)
  - Beta-Delayed Emitters
  - Ground-State Emitters
- Light two-proton emitters: In-Flight decay (Short lifetimes)

Potential two proton emitters



Adapted from M. Thoennessen

Definitions



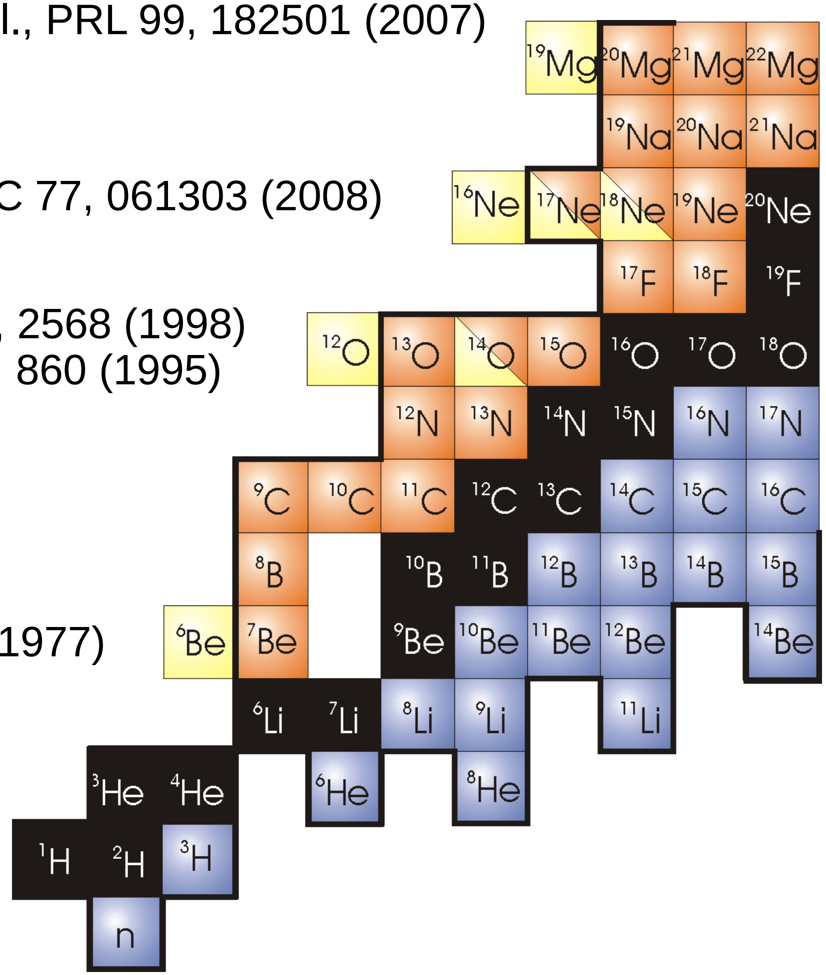
Light two-proton emitters

I. Mukha et al., PRL 99, 182501 (2007)

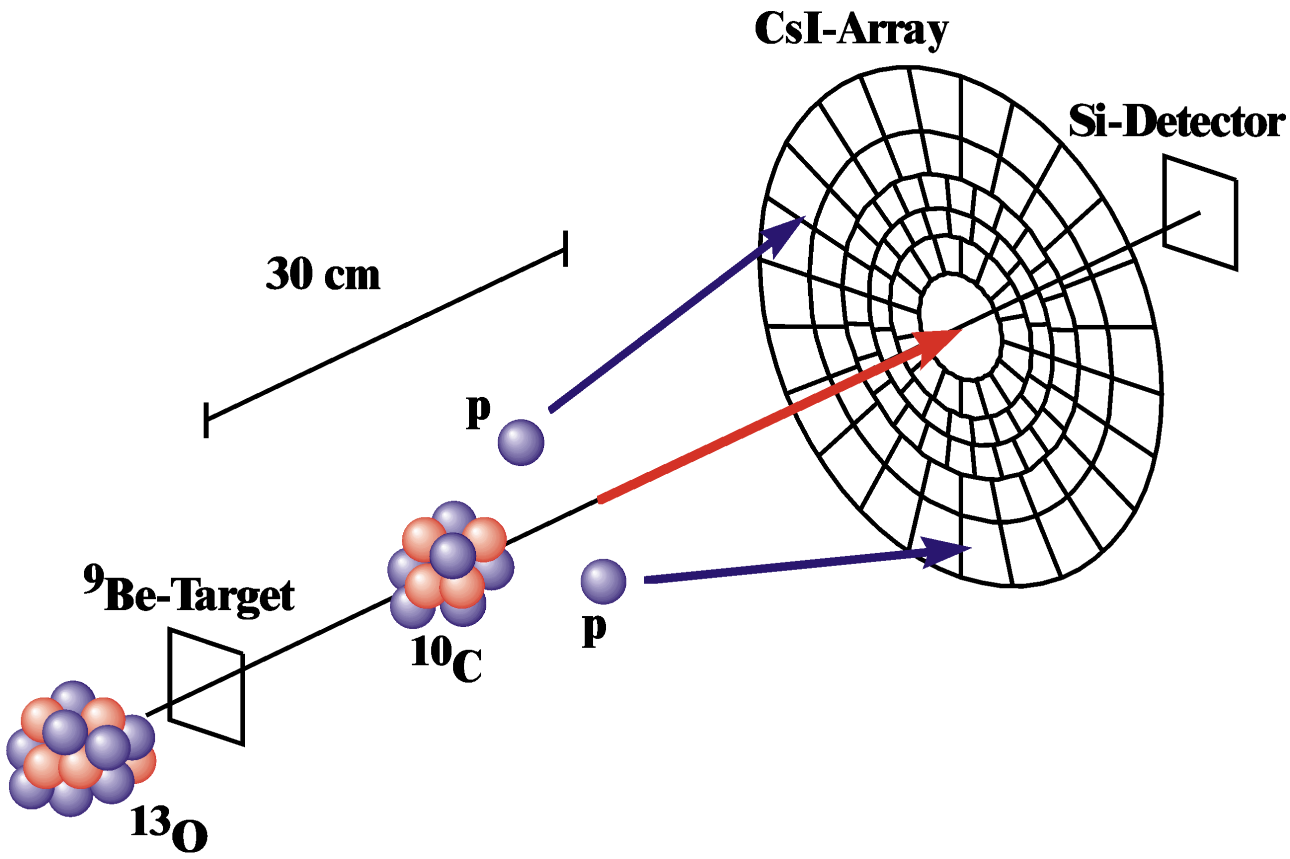
I. Mukha et al., PRC 77, 061303 (2008)

A. Azhari et al., PRC 58, 2568 (1998)
A. Kryger et al., PRL 74, 860 (1995)

D. Geesaman et al., PRC 15, 1835 (1977)

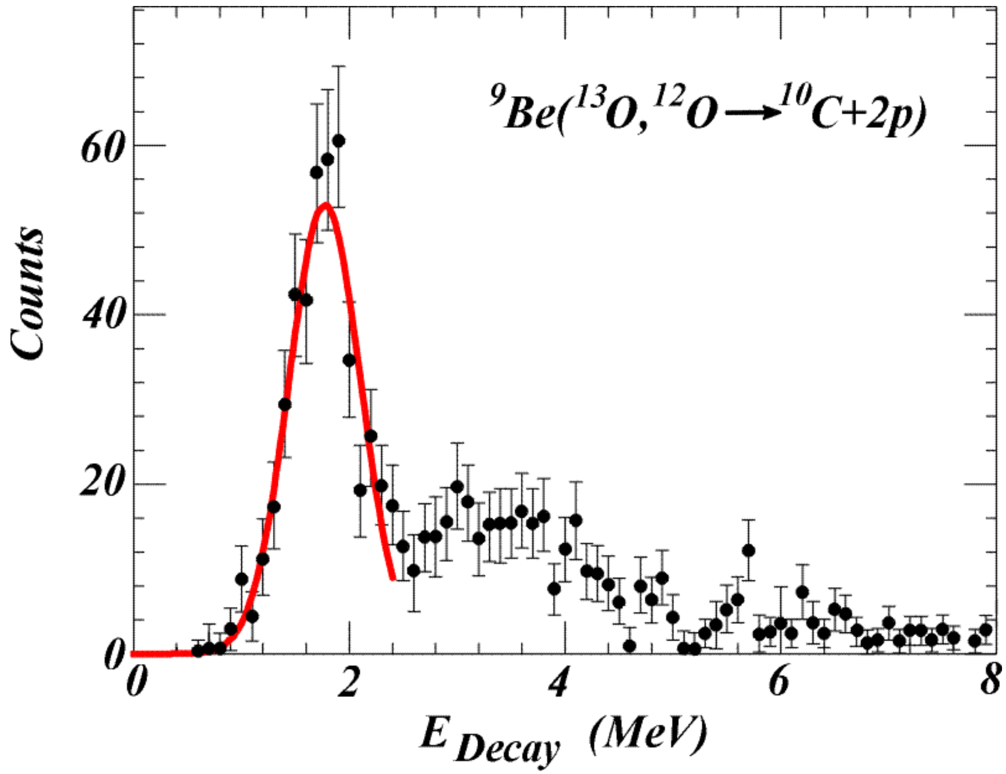


Production and identification of short-lived nuclei



Adapted from M. Thoennessen

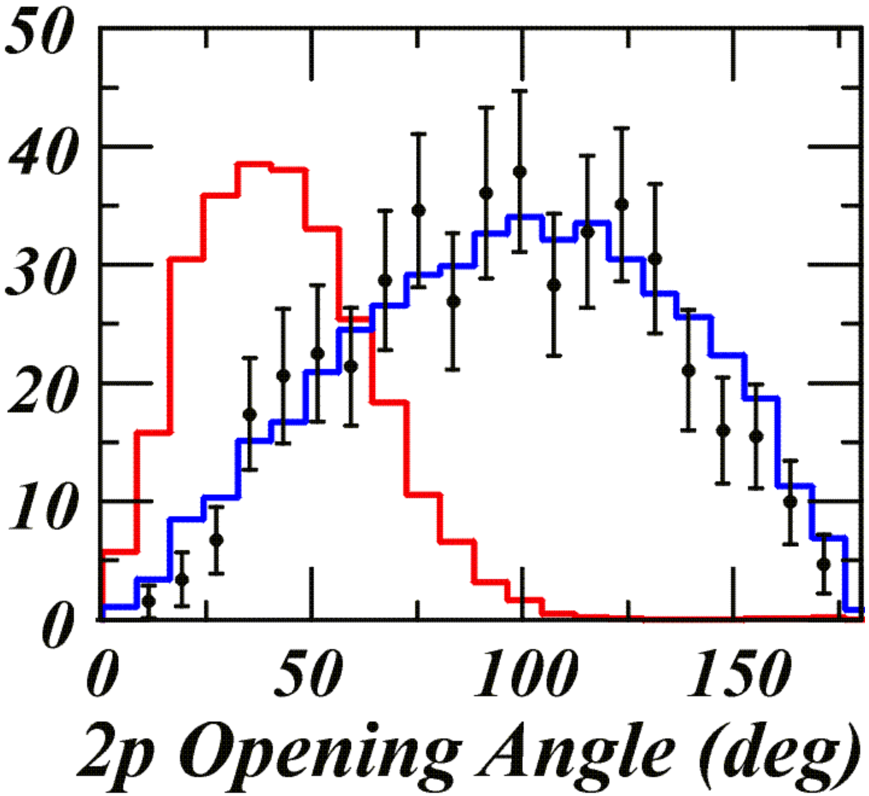
Decay energy spectrum of ^{12}O



E_{Decay} = 1.77(02) MeV Γ = 578(205) keV

R. A. Kryger et al., PRL 74, 860 (1995)

Two-proton angular distribution



R matrix theory

Di-Proton

Di-proton emission (50 keV resonance)

Sequential

3-body decay only restricted by phase space

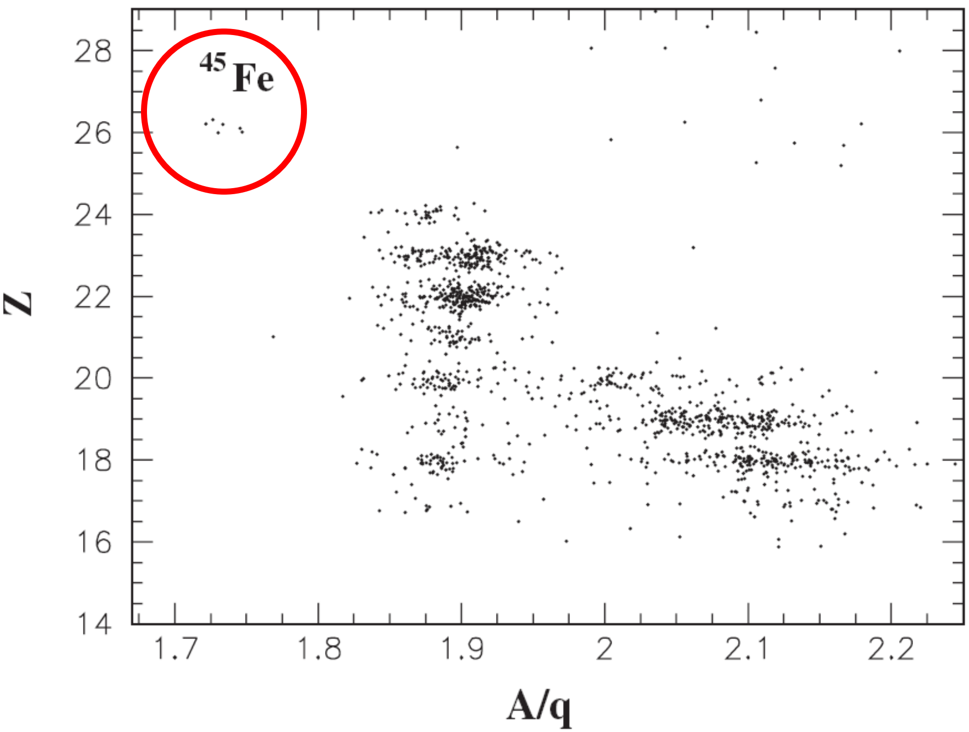
R. A. Kryger et al., PRL 74, 860 (1995)

Two-proton radioactivity
Predictions

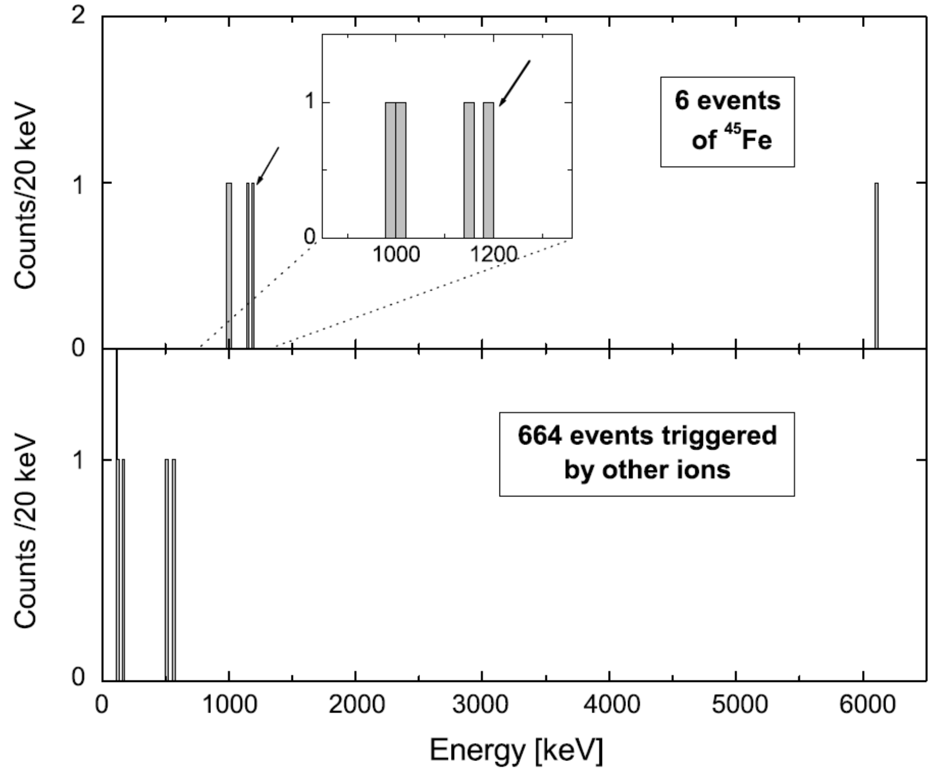
• ^{38}Ti	$(0.4\text{-}2.3)\times 10^{-12}$ ms
• ^{39}Ti	0.4-2000 ms
• ^{45}Fe	$10^{-5}\text{-}10^{-1}$ ms
• ^{48}Ni	0.01-3660 ms
• ^{63}Se	0.3-5000 ms

W. E. Ormand, PRC 55, 2407 (1997)
W. E. Ormand, PRC 53, 2145 (1996)
B. A. Brown, PRC 43, R1513 (1991)

^{45}Fe: 2-Proton Decay at GSI
2002



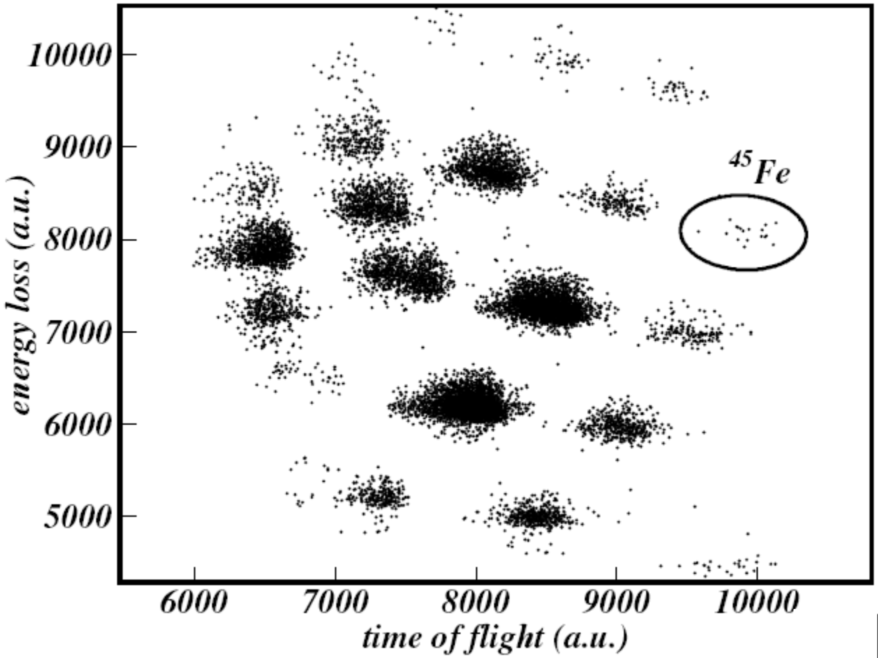
6 events of ^{45}Fe identified, 4 events consistent with the 2p emission ar 1.1(1)MeV and half-life ~3.2 ms



^{45}Fe produced in the fragmentation of ^{58}Ni at 650 MeV/u.

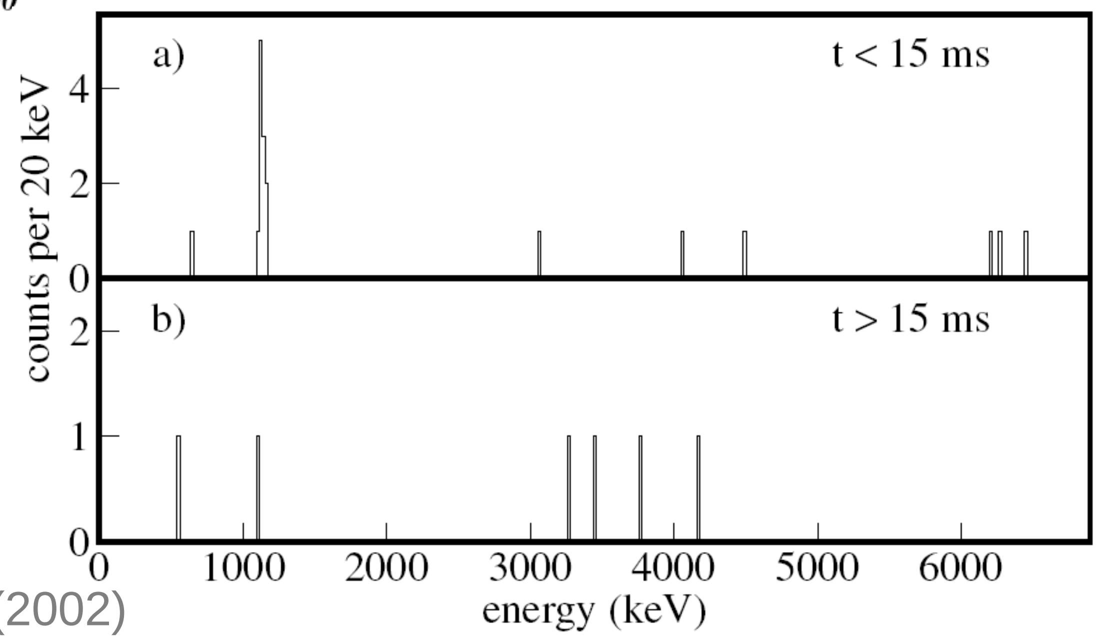
M. Pfützner et al., Eur. Phys. A 14, 279 (2002)

^{45}Fe: 2-proton decay at GANIL *2002*



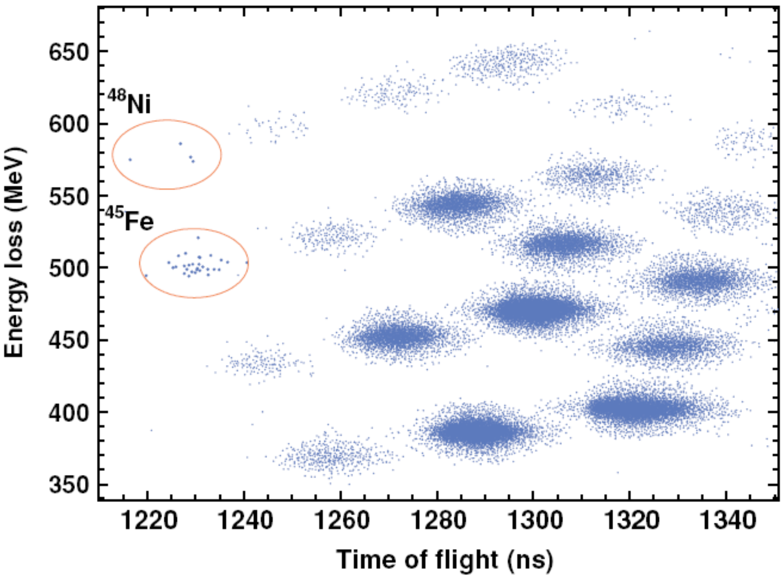
22 events of ^{45}Fe identified, 12 events consistent with the 2p emission at 1.14(4) MeV and half-life ~4.7 ms

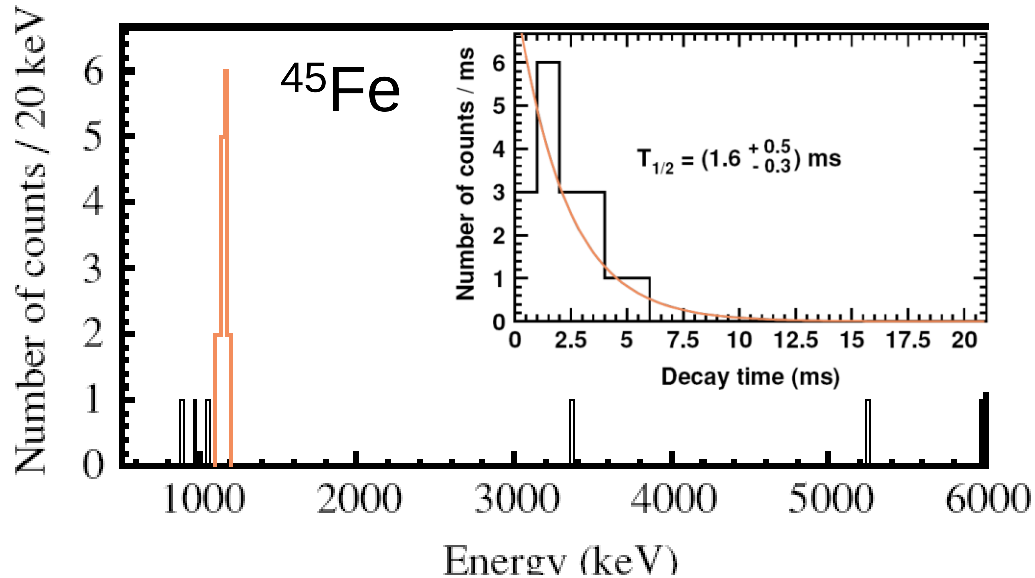
^{45}Fe produced in the fragmentation of ^{58}Ni at 75 MeV/u

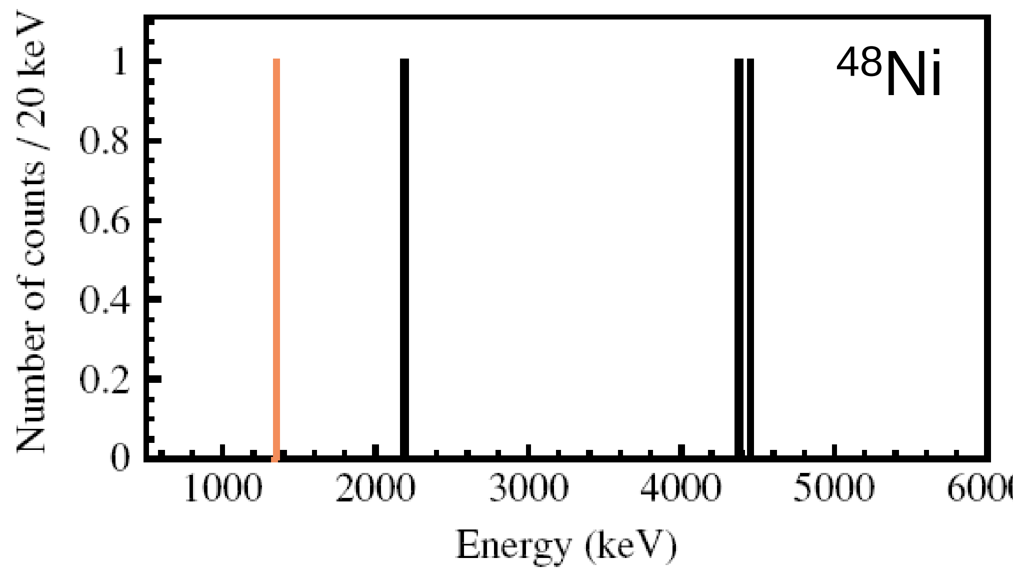


J. Giovinazzo et al., PRL 89, 102501 (2002)

^{45}Fe and ^{48}Ni: 2-proton decay at GANIL *2005*



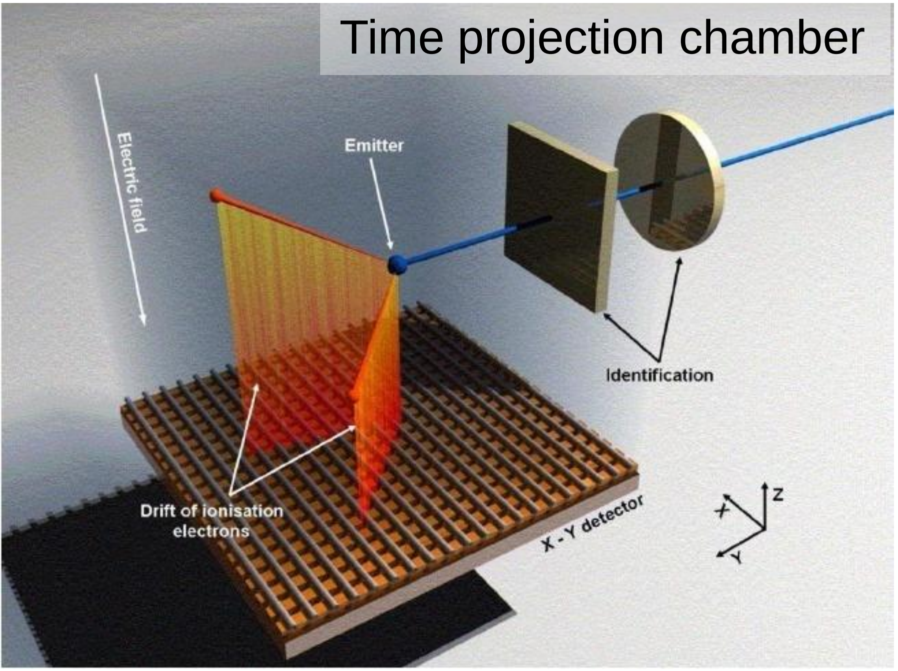


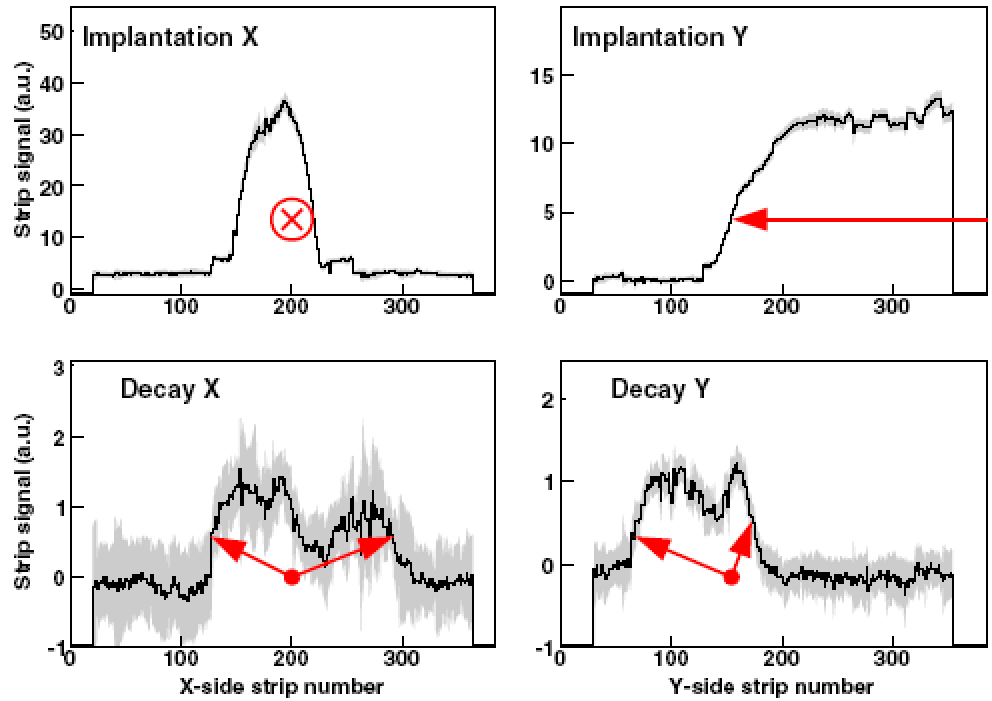


30 events of ^{45}Fe and 4 of ^{48}Ni identified. 17 ^{45}Fe events were consistent with the 2p emission at 1.154(16) MeV and half-life ~1.6(4) ms

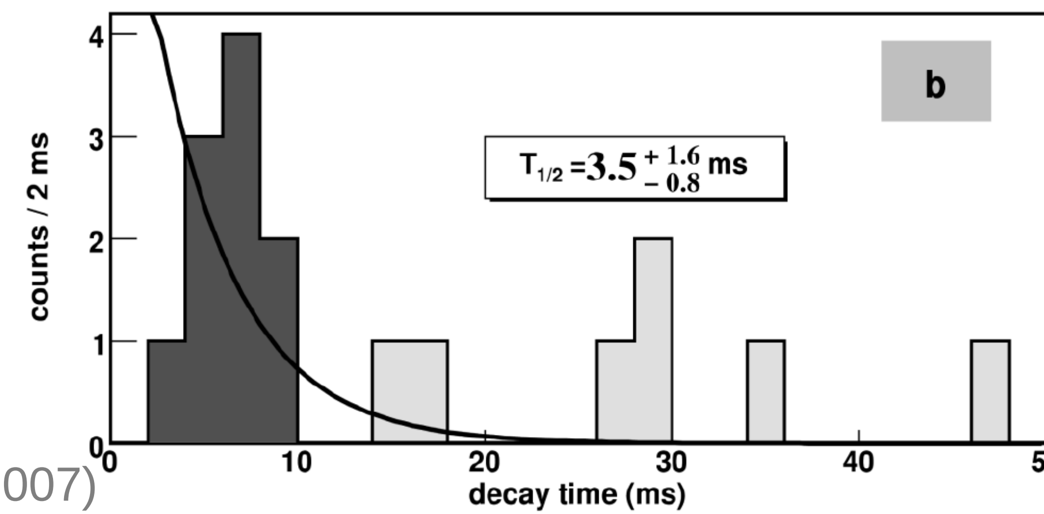
C. Dossat et al., PRC 72, 054315 (2005)

^{45}Fe: 2-proton decay at GANIL (again) *2007*





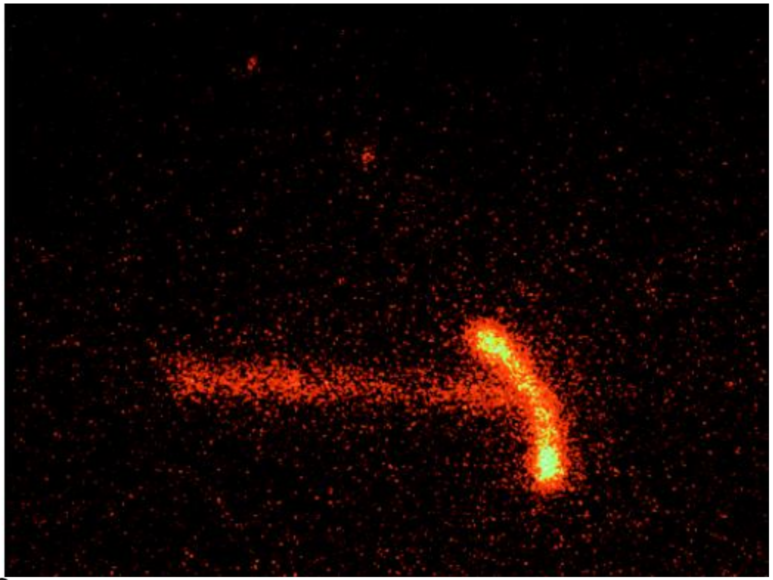
^{45}Fe produced in 75 MeV/u ^{58}Ni fragmentation. Identification of the two protons in a time projection chamber. First direct observation of the two protons



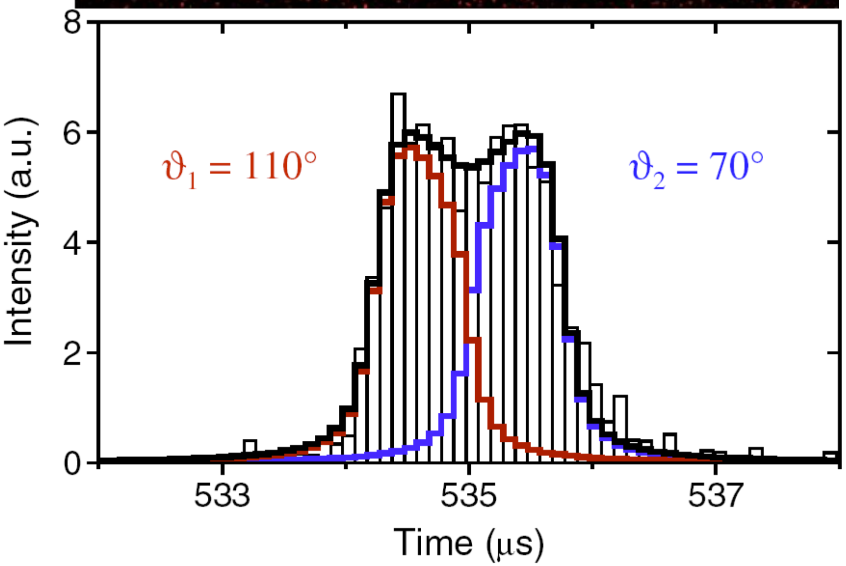
J. Giovinazzo et al., PRL 99, 102501 (2007)

^{45}Fe: 2-proton decay in OTPC at NSCL *2007*

^{45}Fe 2p-decay caught in the act



Recorded by CCD camera (25 ms exposure). ^{45}Fe enters from the left, short tracks are protons (~ 600 keV) emitted 535 μs after implantation



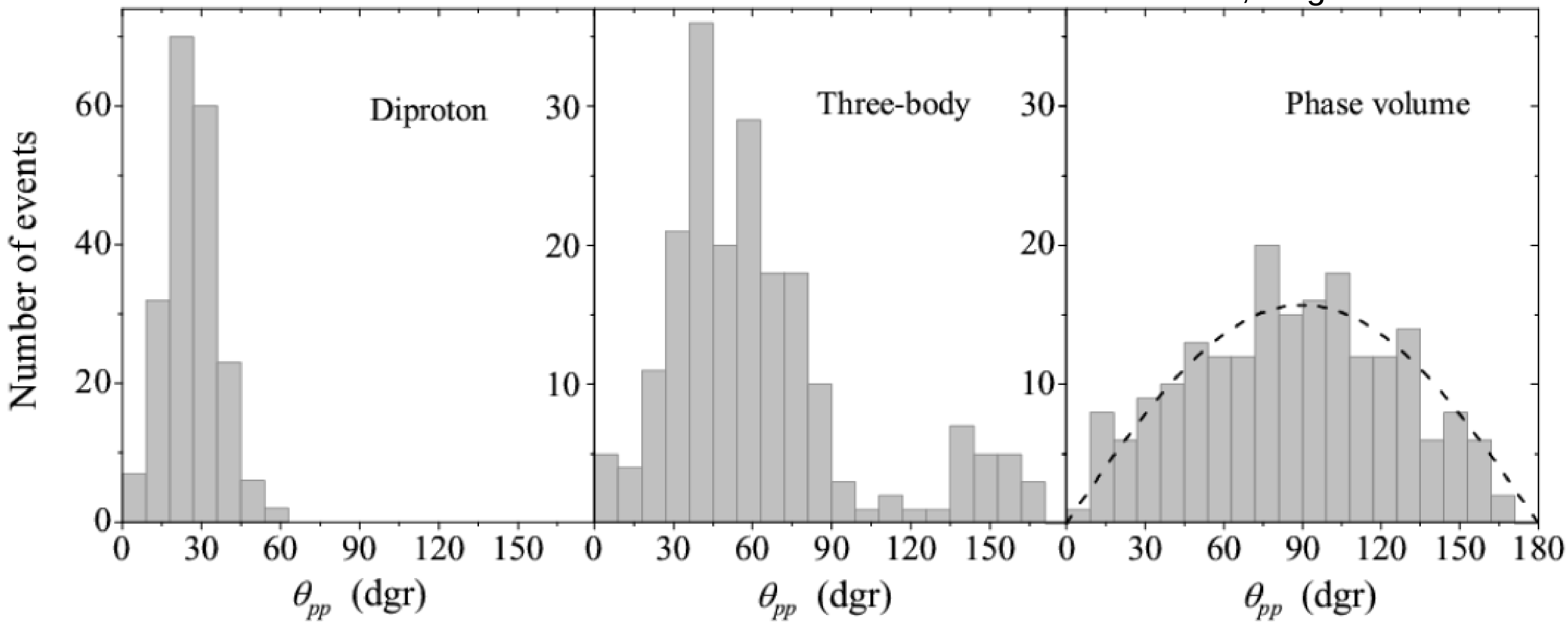
Time profile of the total light intensity measured by photomultiplier tube

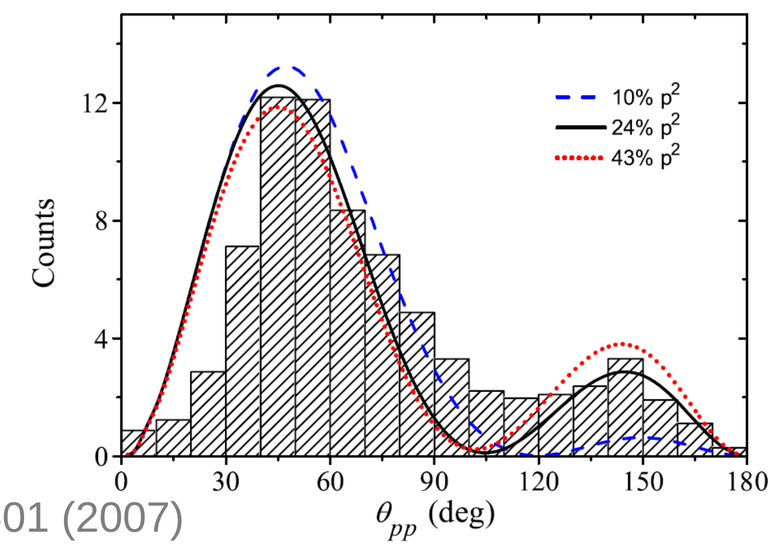
2p radioactivity but no simple ^{2}He (di-proton) picture

K. Miernik et al., PRL 99, 192501 (2007)

^{45}Fe: Correlation of the protons?

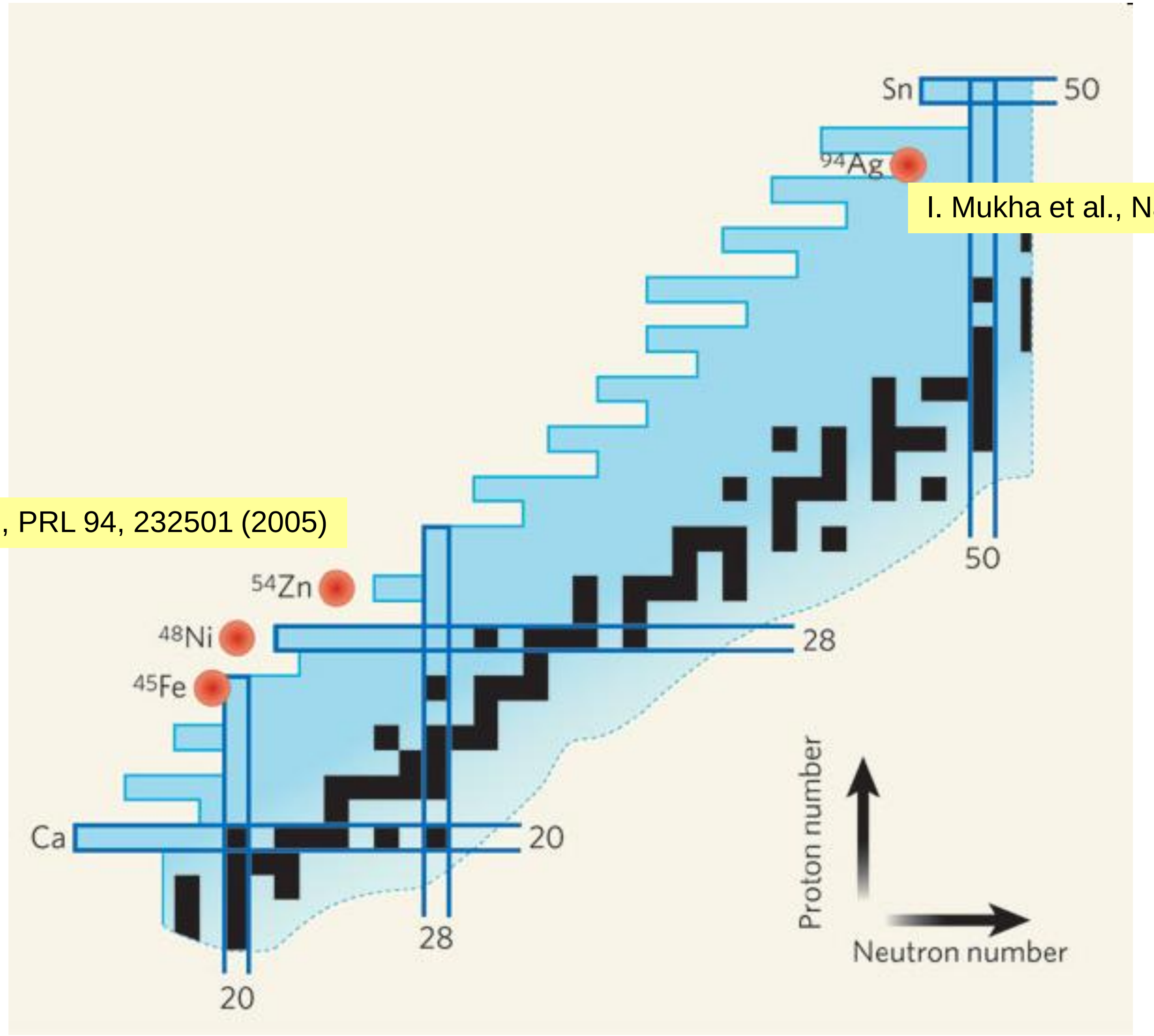
Pfutzner, Grigorenko et al.





K. Miernik et al., PRL 99, 192501 (2007)

Two-proton radioactivity
So far



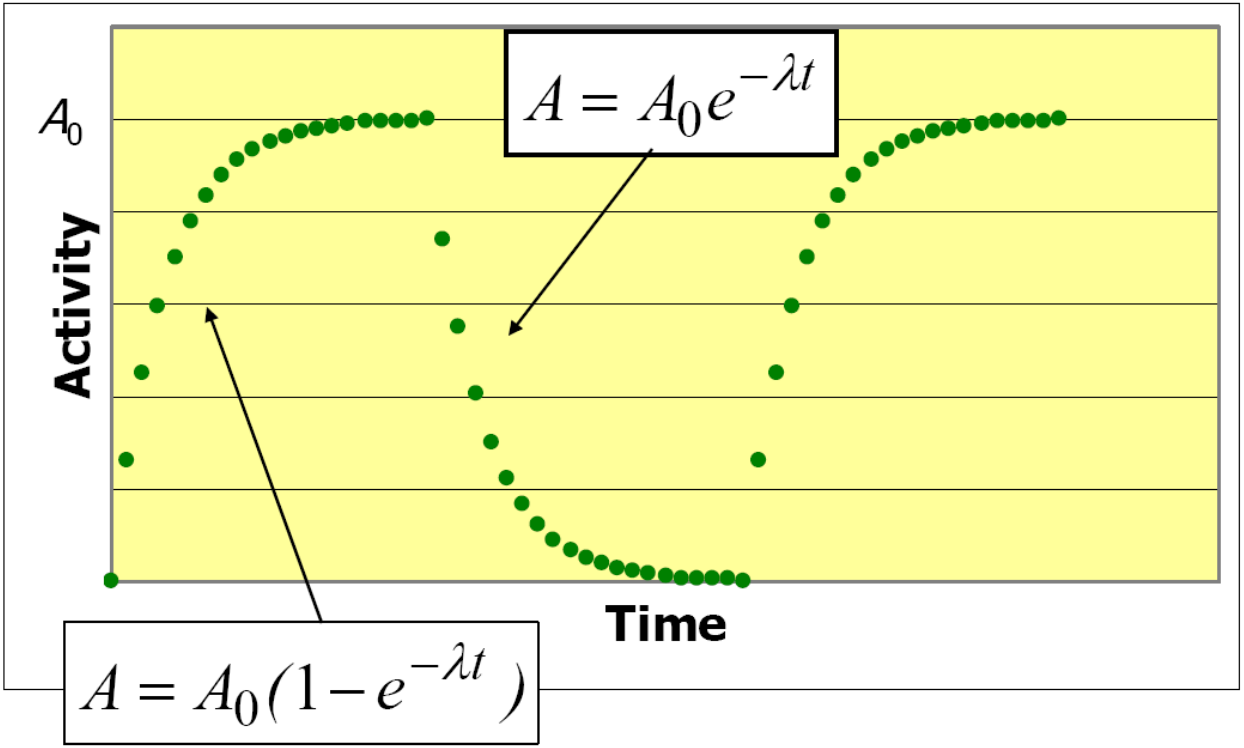
I. Mukha et al., Nature 439, 298 (2006)

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

J. Aysto, News and Views, Nature 439, 279 (2006)

Half-lives

β-decay bulk activity measurements



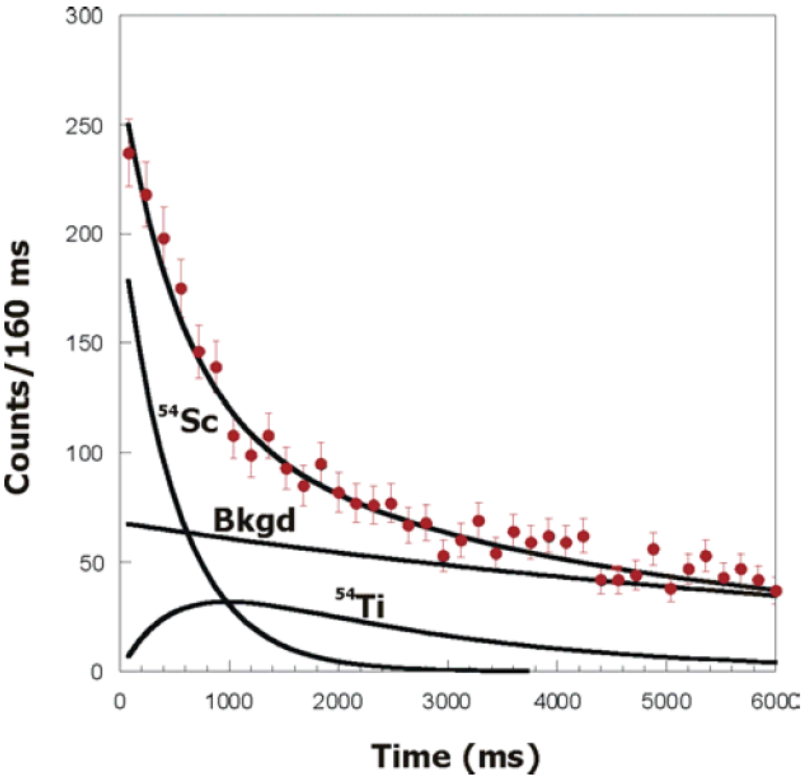
$\lambda = \ln 2 / t_{1/2}$

$t_i = t_d = 4 \times t_{1/2}$

Implant activity in active stopper material for time t_i. Cease implantation and observe decay for time t_d.

Adapted from P. F. Mantica

Event-by-event correlation technique



Production rate: 0.5 ^{54}Sc/s

^{54}Sc

$T_{1/2}$ = 360±60 ms

^{54}Ti

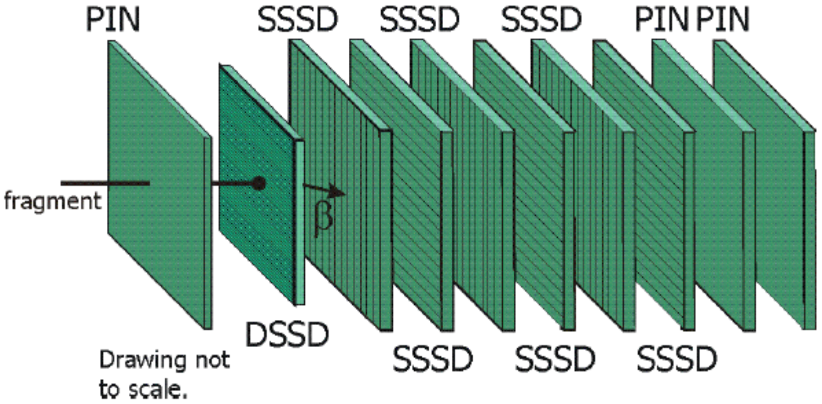
- **Reduced background from in-flight tracking and identification of individual isotopes in the beam on a particle-by-particle basis**

Adapted from P. F. Mantica

Janssens, Broda, Mantica *et al.*, PLB546, 55 (2002)

Beta counting systems
Example: BCS at NSCL

NSCL Beta Counting System and Calorimeter



Permits the correlation of fragment implants and subsequent beta decays on an event-by-event basis

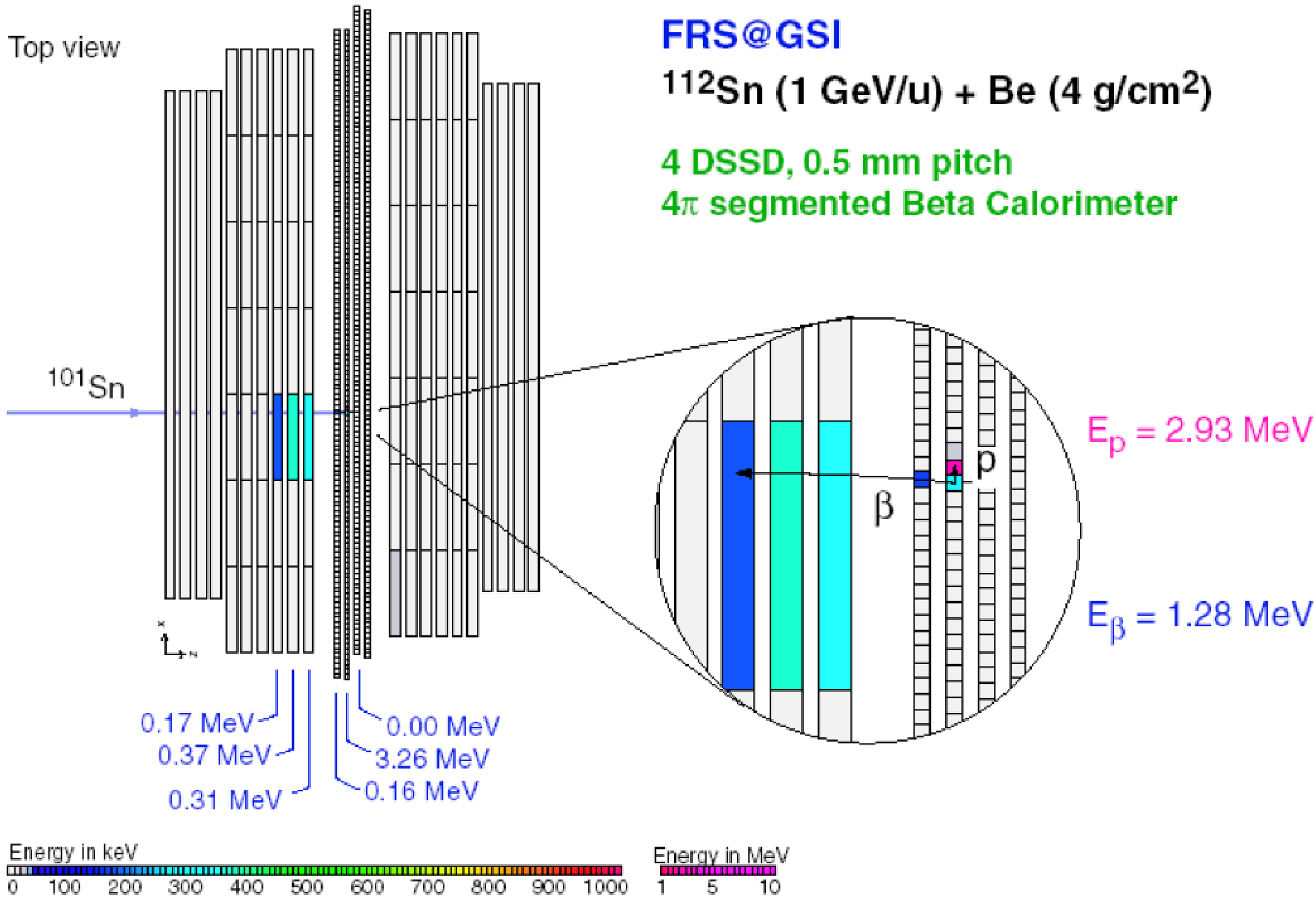
Implant detector: 1 each MSL type BB1-1000
- **4 cm x 4 cm active area**
- **1 mm thick**
- **40 1-mm strips in x and y**

Calorimeter: 6 each MSL type W
- **5 cm active area**
- **1 mm thick**
- **16 strips in one dimension**

Prisciandaro *et al.*, NIMA **505** (2003) 140.

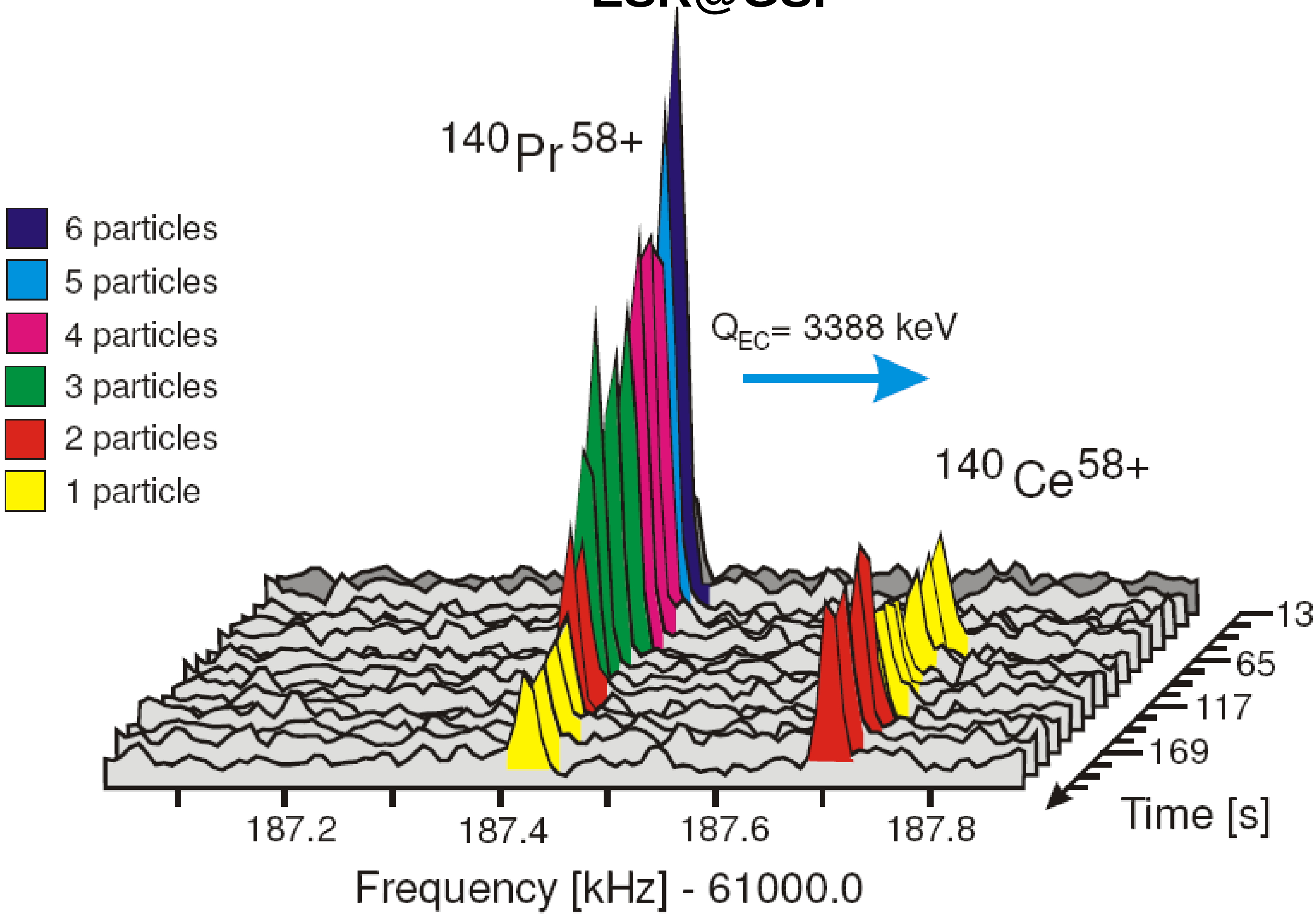
Adapted from P. F. Mantica

^{101}Sn β-decay



A. Stolz (2003)

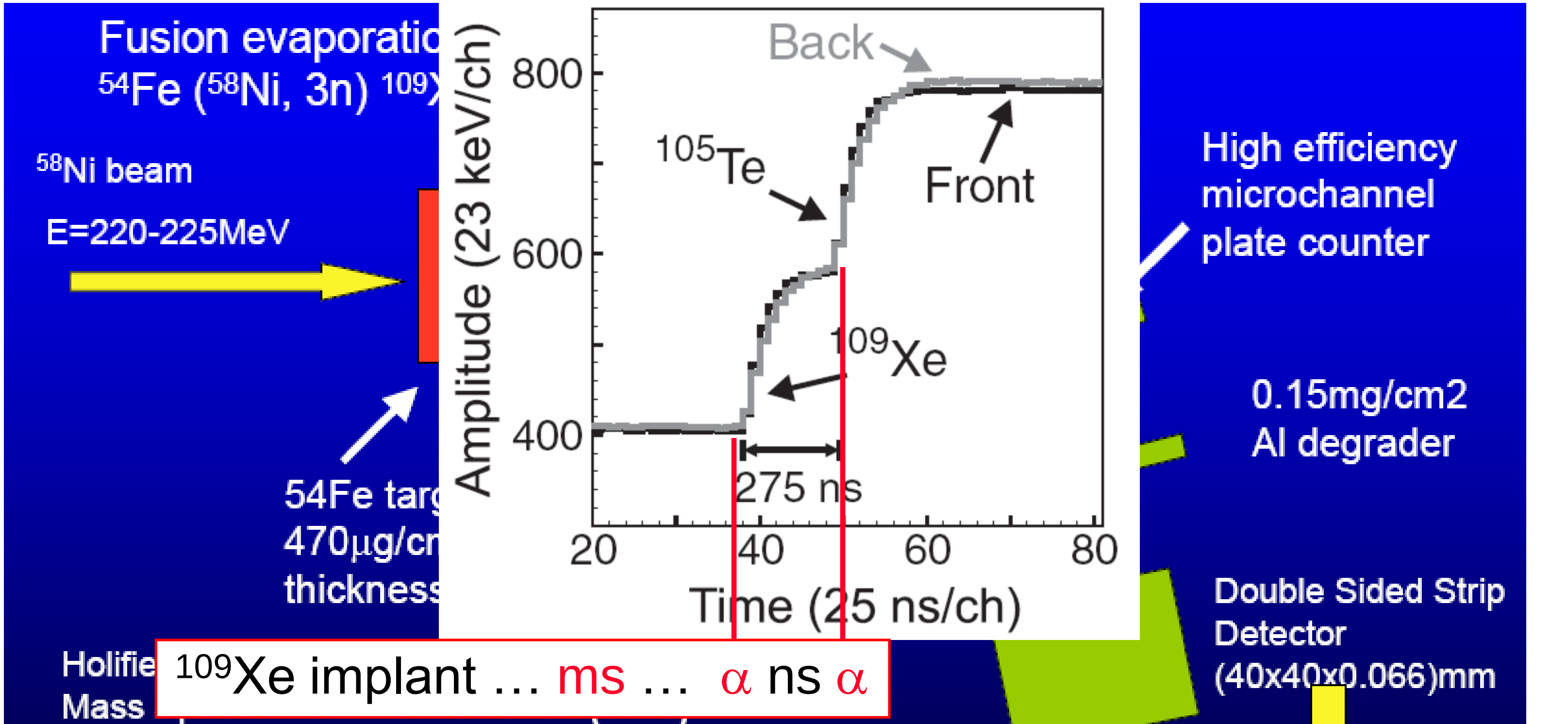
Caught in the act: $^{140}Pr \rightarrow {}^{140}Ce$ electron capture in the ESR@GSI

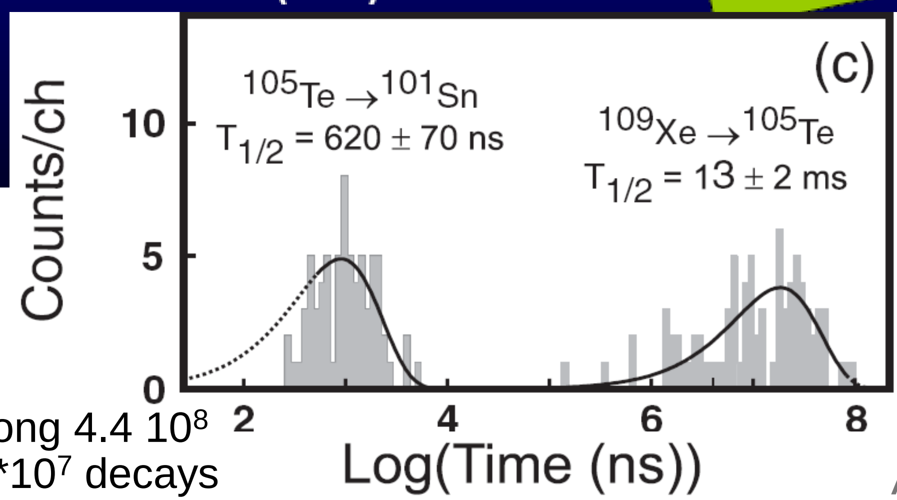


F. Bosch et al. Int. J. Mass Spectr. 251 (2006) 212

$^{109}Xe \rightarrow {}^{105}Te \rightarrow {}^{101}Sn$ α-decay chain
Digital DAQ (HRIBF@ORNL)

S.N. Liddick et al., PRL 97, 082501 (2006)





identify 100 events among 4.4 10^8 implanted ions and $1.7*10^7$ decays

Adapted from S. N. Liddick

Take away

- Experiments to establish the neutron dripline are hard. And the dripline might be further out than expected ... More exciting physics to be discovered!
- Spectroscopy beyond the proton dripline gives information on nuclear structure and proton-proton correlation
- Different ways to measure half-lives of short-lived nuclei
    - Bulk-activity measurements
    - Event-by-event correlation technique
    - Storage rings again

Related review articles

The driplines

- Reaching the limits of nuclear stability, M. Thoennessen, Rep. Prog. Phys. 67, 1187 (2004)

Proton radioactivity

- Two-proton radioactivity, B. Blank and M. Ploszajczak, Rep. Prog. Phys. 71, 046301 (2008)
- Nuclear structure at the proton drip line: Advances with nuclear decay studies, B. Blank and M.J.G. Borge, Prog. Part. Nucl. Phys. 60, 403 (2008)
- Nuclei beyond the proton drip-line, P. J. Woods and C. N. Davids, Annu. Rev. Nucl. Part. Sci. 47, 541 (1997)

Beta decay halflives

- *β and isomer spectroscopy of neutron-rich nuclei with* fragmentation beams at the NSCL, P. F. Mantica, J. Phys. G: Nucl. Part. Phys. 31 (2005) S1617–S1622