Nuclear Structure Experiments I

Monday

Preliminaries

Nuclear existence

Decay modes beyond the driplines

Ground-state half-lives

(Masses → Guy Savard's lectures)

Tuesday

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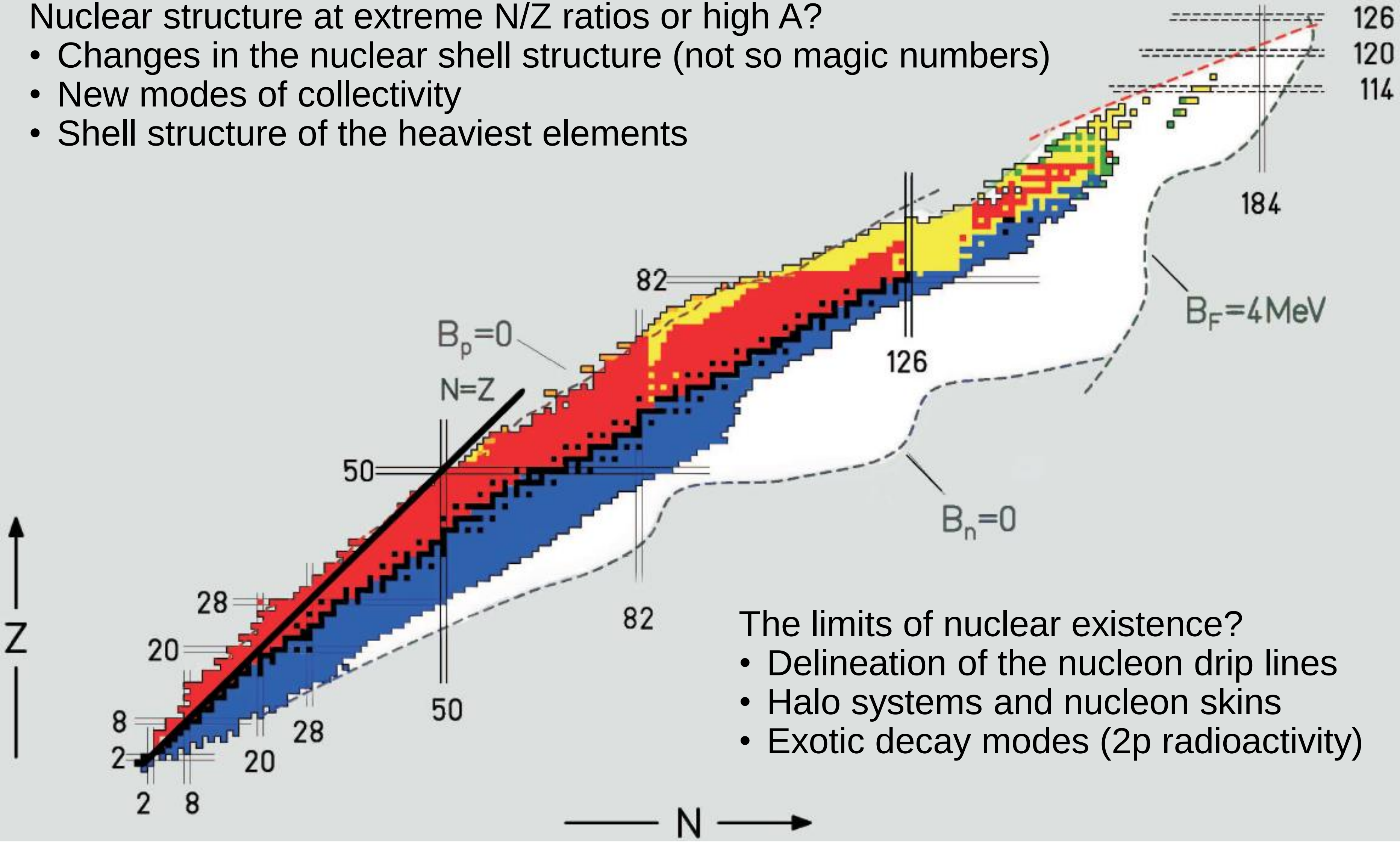
Many observables need to be measured to tackle the challenges outlined in previous presentation

Nuclear structure at extreme N/Z ratios or high A?

- Changes in the nuclear shell structure (not so magic numbers)
- New modes of collectivity
- Shell structure of the heaviest elements



The limits of nuclear existence?

- Delineation of the nucleon drip lines
- Halo systems and nucleon skins
- Exotic decay modes (2p radioactivity)

Preliminaries (1)

Goal: Establish physical properties of rare isotopes and their interactions to gain predictive power

Experiments: Measure observables

Observables: May or may not need interpretation to relate to physical properties

- e.g., half-life and mass connect directly to physical properties
- e.g., cross sections for reaction processes usually need interpretation to connect to physical properties (model dependencies are introduced)

Preliminaries (2)

Theories and models can relate observables to physical properties – often, experiments are motivated by theoretical predictions that need validation

But: Theories and models have their own realm of applicability that everybody involved in the experiment/data analysis/interpretation should be aware of!

Predictions or systematics come with a warning: Might lead to expectations that can influence the implementation of an experiment and ultimately limit the scope of discovery

Preliminaries (3)

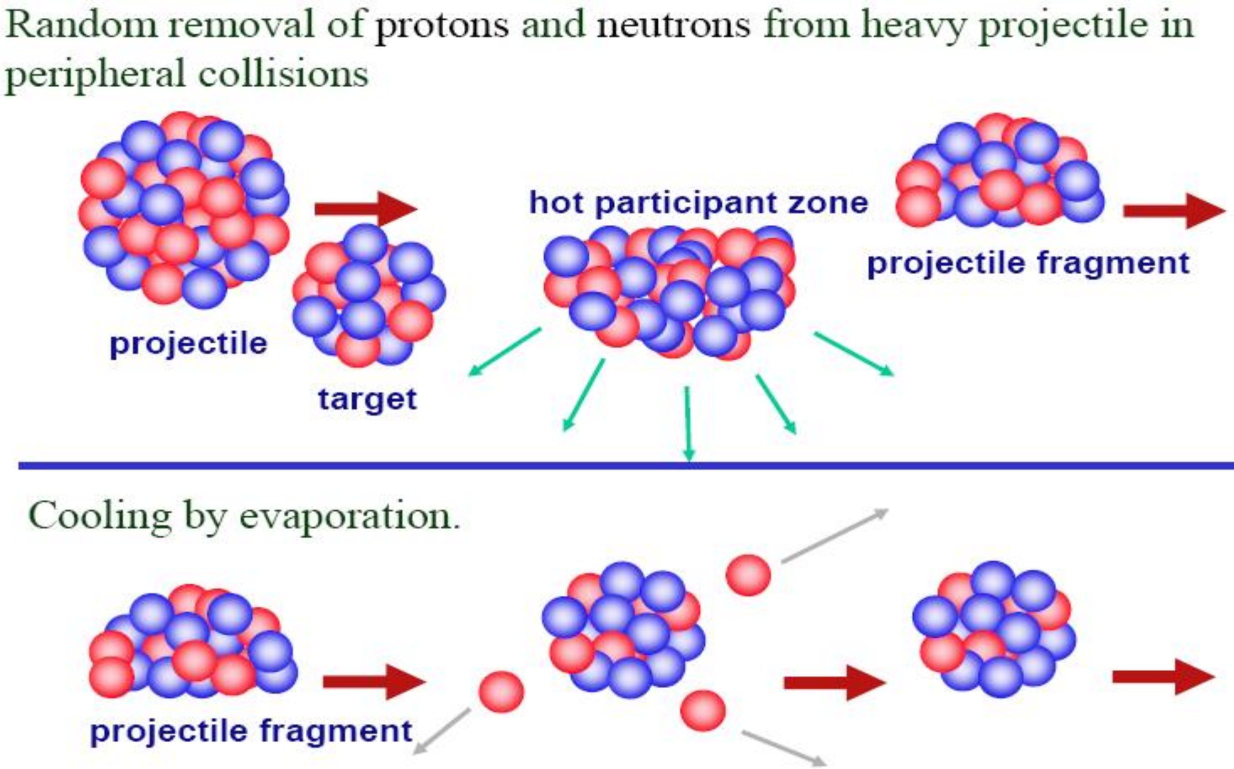
Nuclear physics experiments are complex and experiments with rare isotopes pose additional challenges

- Rare isotopes are typically available for experiment as beams of ions

- Many of the established and well-tested techniques are not applicable and new approaches have to be developed

Details in the lectures by S. Pain, D. Bazin and A. Wuosmaa

Production of exotic nuclei


Random removal of protons and neutrons from heavy projectile in peripheral collisions

Cooling by evaporation.

- •Transfer reactions
- •Fusion-evaporation
- •Fission
- •Fragmentation
  - Target fragmentation (TRIUMF, ISOLDE, SPIRAL, HRIBF)
  - Projectile fragmentation (NSCL, GSI, RIKEN, GANIL)

You will work with rare isotopes produced by fragmentation in your hands-on activity!

Limits of existence – the neutron and proton driplines

- Limits of existence – neutron dripline
- The dripline is a benchmark that all nuclear models can be measured against
- Nuclear structure is qualitatively different (halo structures and skins)
- Sensitive to aspects of the nuclear force (see theory lectures)

North on the nuclear chart: The limit of mass and charge

Lecture by K. Rykaczewski on superheavy elements

Location of the driplines

Experimental task: How to find a needle in a haystack

How many neutrons can a proton bind?

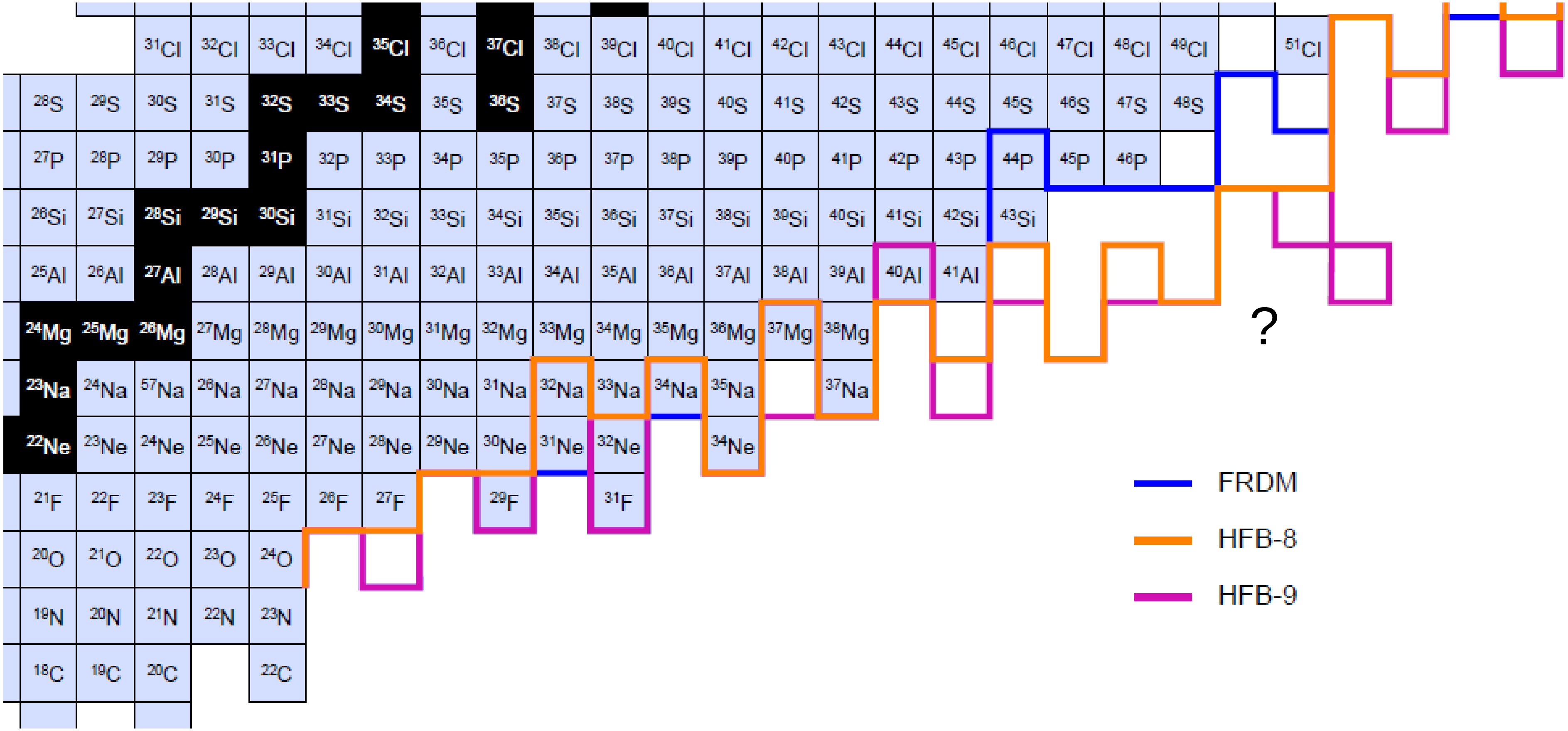
The limit of nuclear existence is characterized by
the nucleon driplines

- 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.“

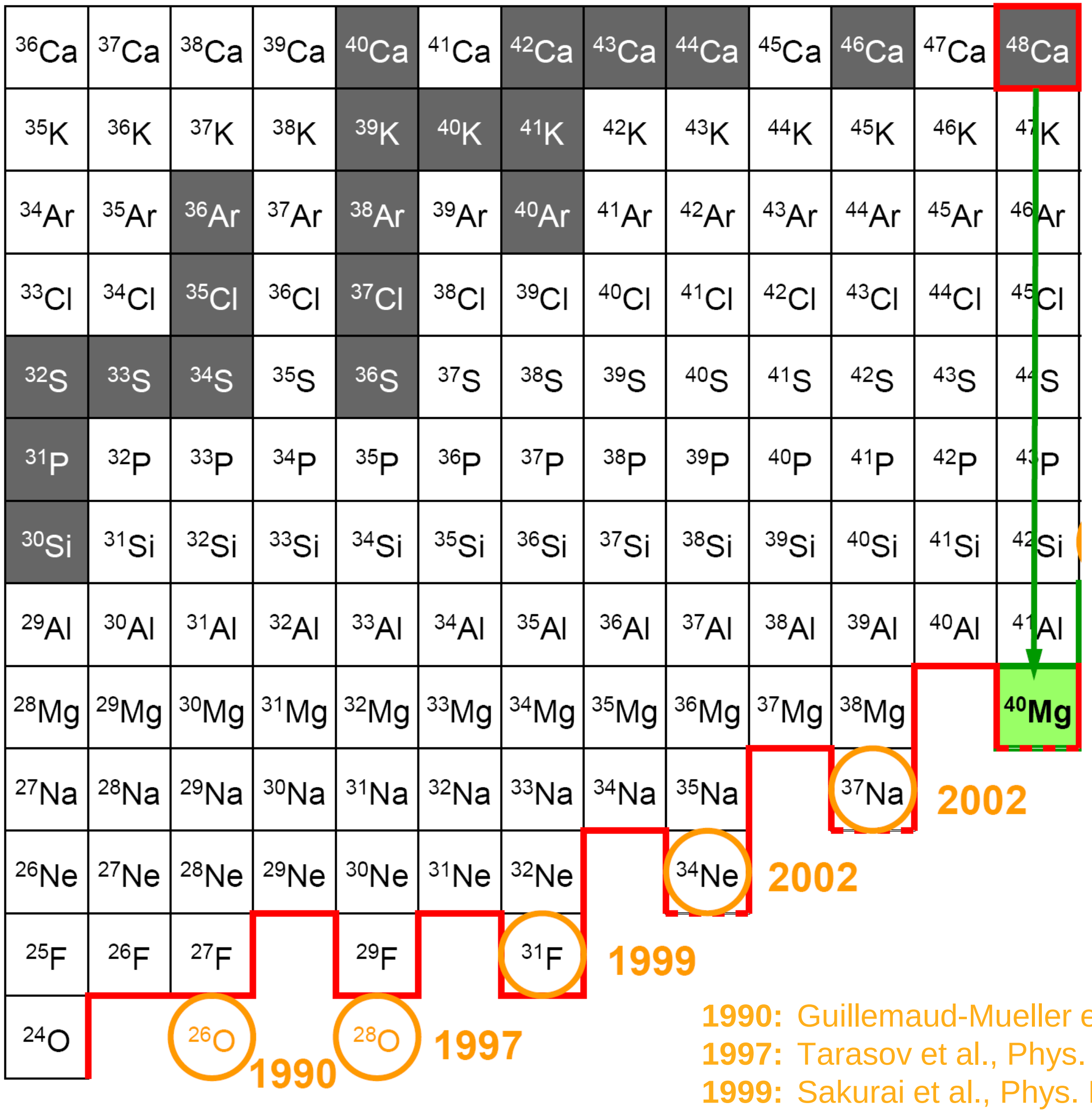
- P. G. Hansen & J. A. Tostevin: "(the dripline is) where the nucleon separation energy goes to zero."

Where is the neutron dripline?

Predictive power, anybody?

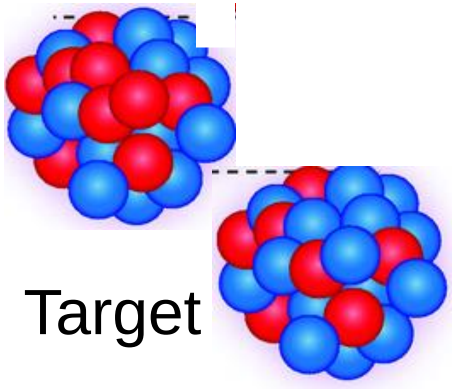


Dripline history and a plan …



^{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								

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

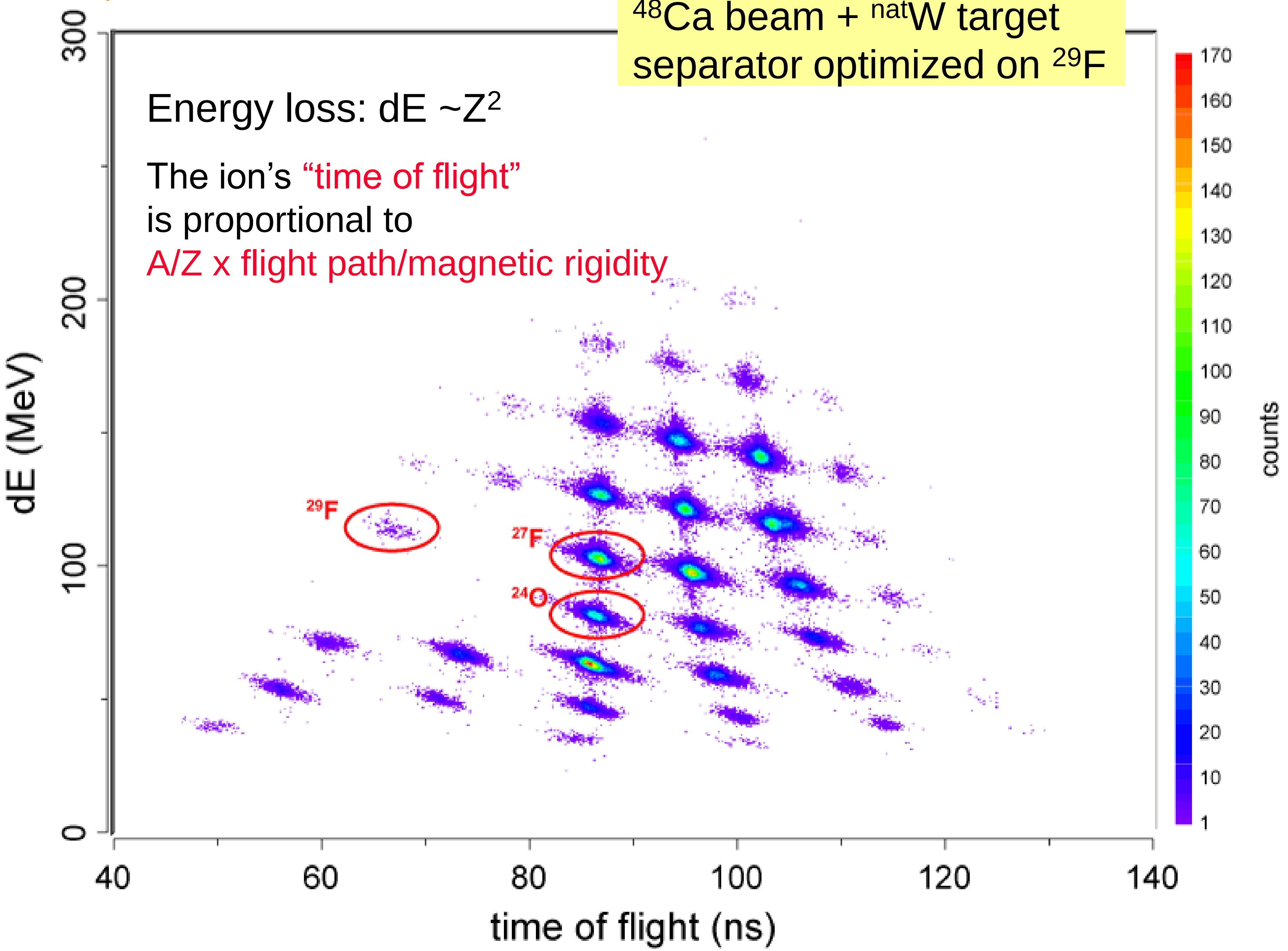


Production of ^{40}Mg from ^{48}Ca:
Net loss of 8 protons with no neutrons removed!

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!

^{48}Ca beam + ^{nat}W target
separator optimized on ^{29}F

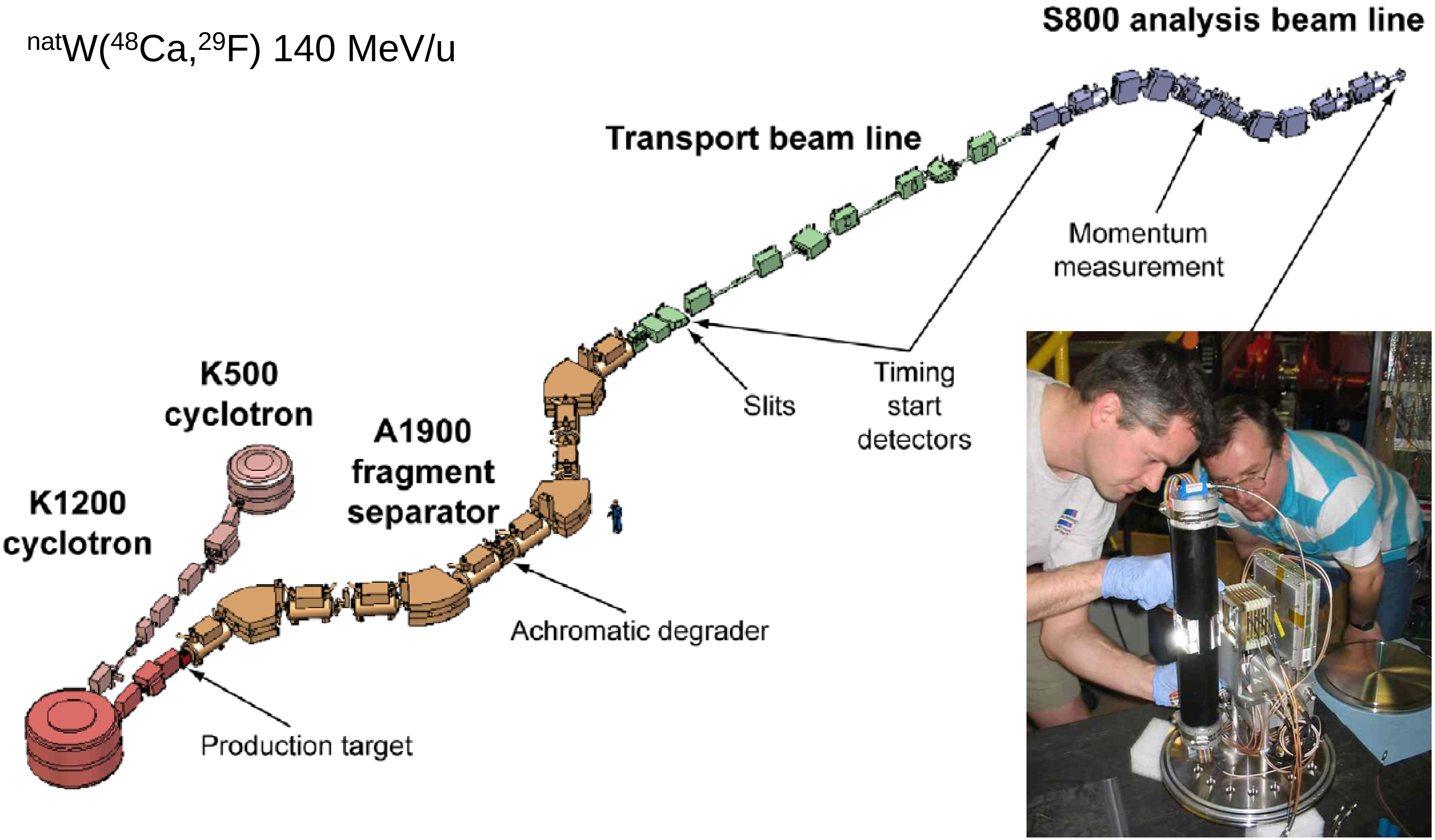


Energy loss: dE ~Z^2

The ion’s “time of flight”
is proportional to
A/Z x flight path/magnetic rigidity

Search for new isotopes – how?

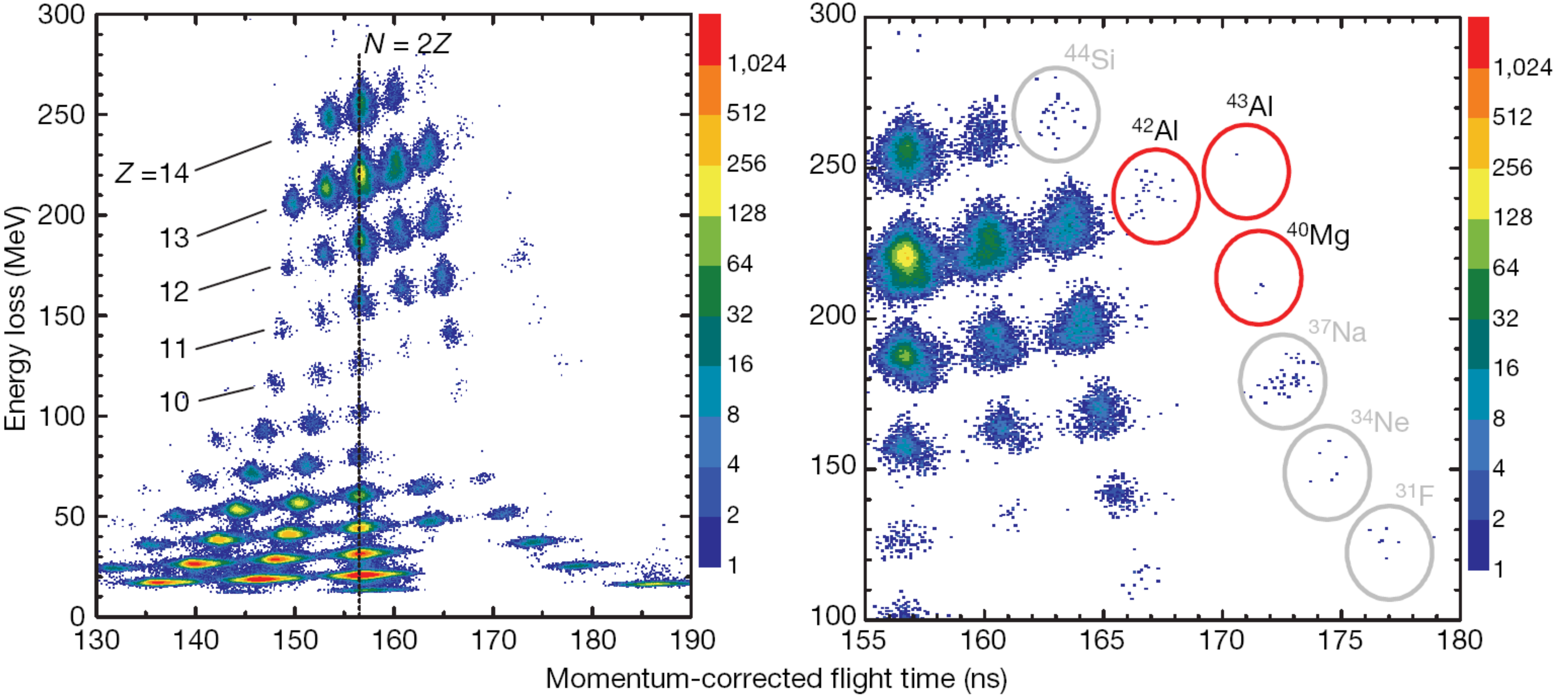
$^{nat}W(^{48}Ca,^{29}F)$ 140 MeV/u



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

^{40}Mg and more!

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



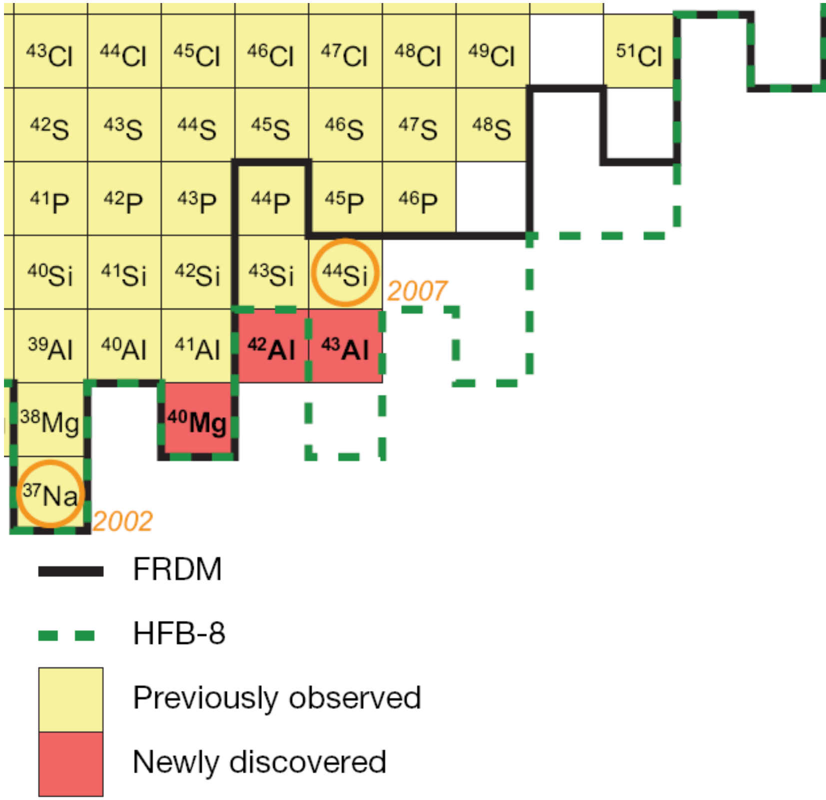
Data taking: 7.6 days at 5 x10^{11} particles/second

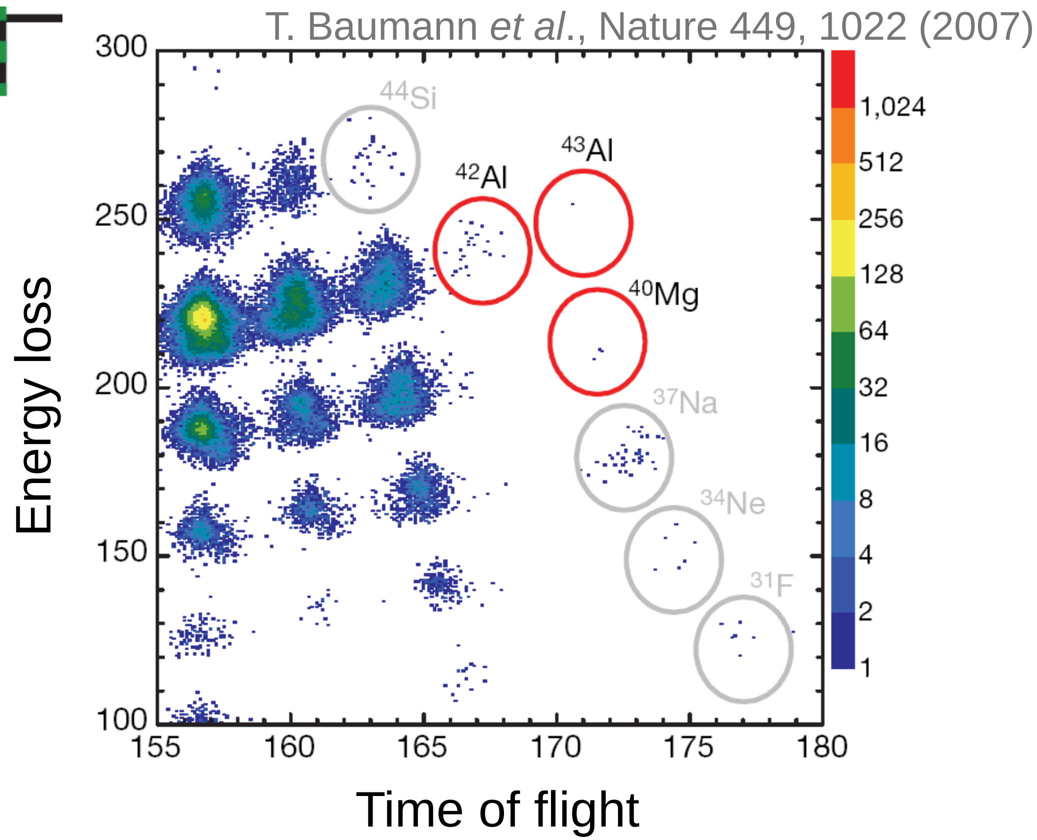
3 events of ^{40}Mg

23 events of ^{42}Al

1 event ^{43}Al

^{40}Mg and more!





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

Data taking: 7.6 days at 5 x10^{11} particles/second

3 events of ^{40}Mg

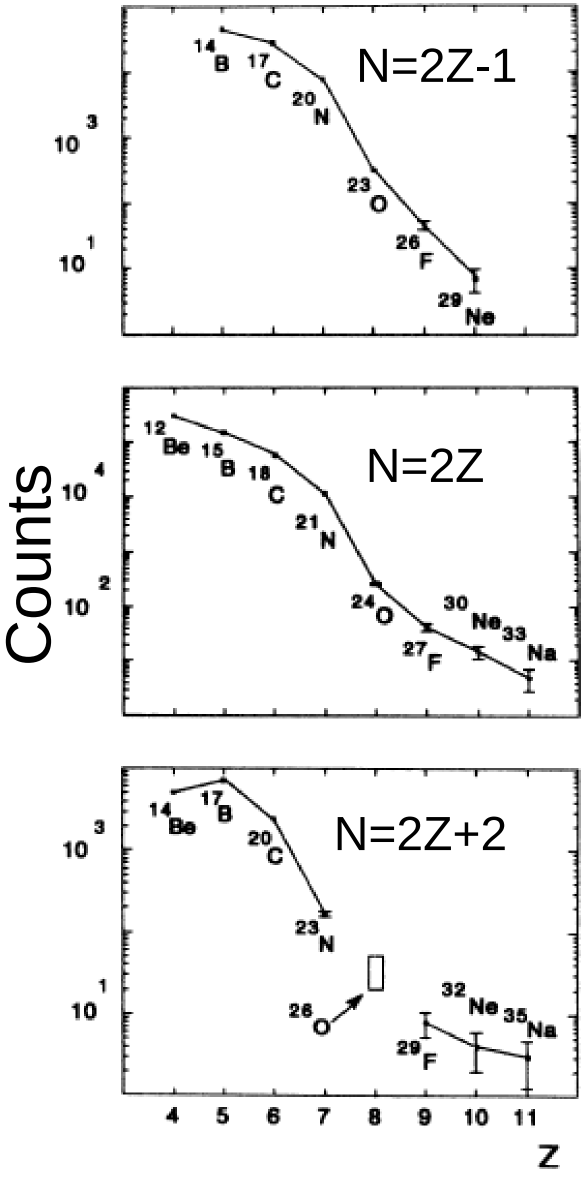
23 events of ^{42}Al

1 event ^{43}Al

The existence of ^{42,43}Al 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

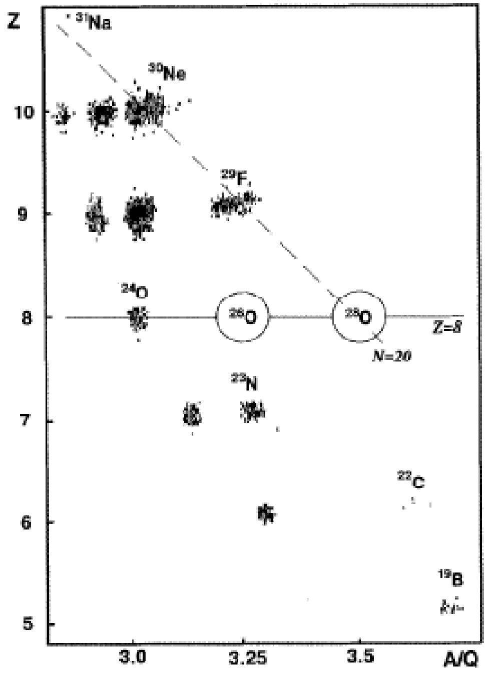
Guillemaud-Mueller et al., PRC 41, 937 (1990)



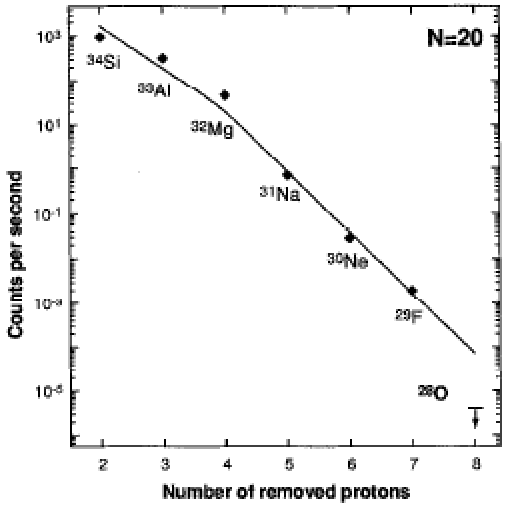
^{48}Ca on Ta
at 44 MeV/u
(GANIL)

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

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



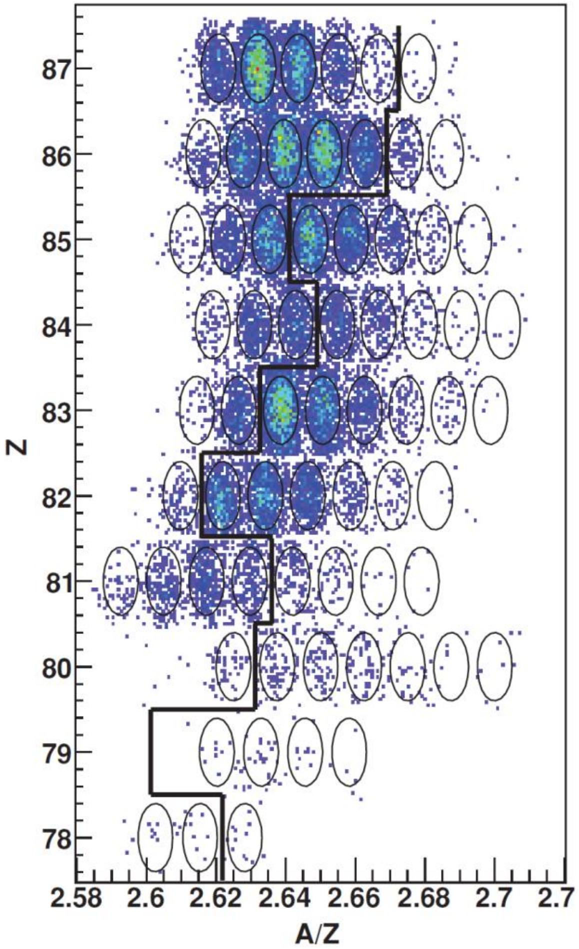
^{36}S on Ta
at 78 MeV/u
(GANIL)



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

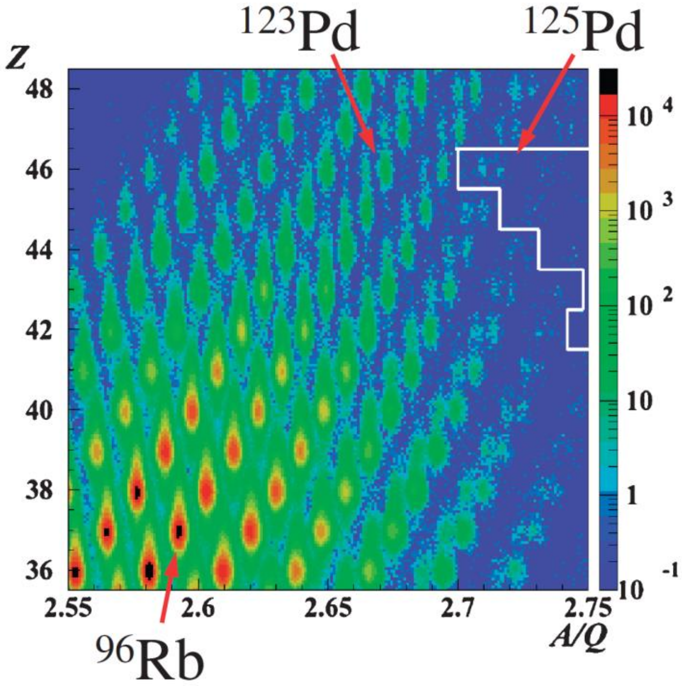
Discovery of new isotopes around the world

Fragmentation of ^{238}U at GSI



H. Alvarez-Pol *et al.*, PRC 82, 041602(R) (2010).

In-flight fission of ^{238}U at RIKEN



T. Ohnishi *et al.*, J. Phys. Soc. Jpn. 77, 083201 (2008).

Decay modes at the proton drip line

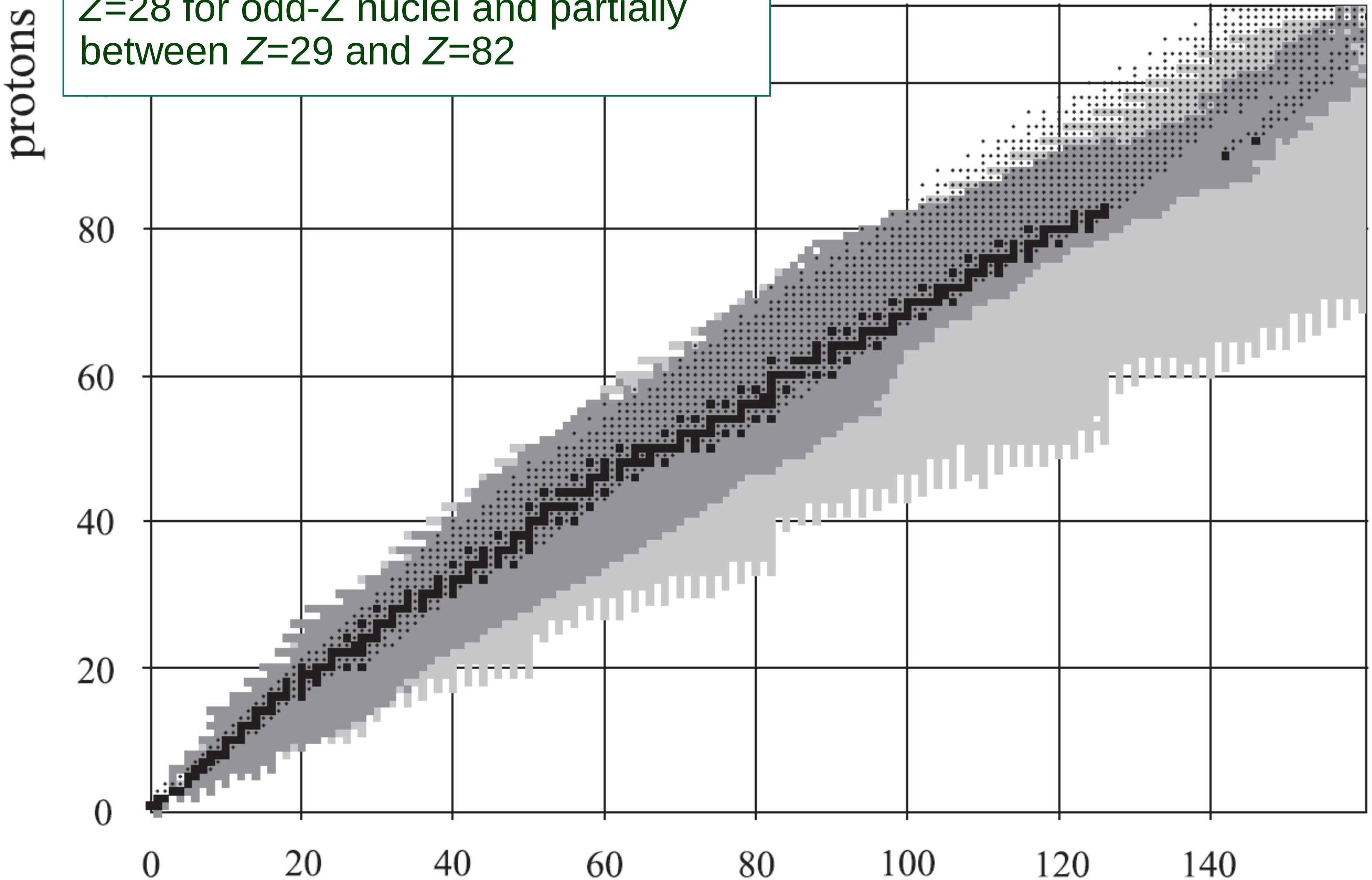
One-proton radioactivity – Direct proton emission from ground states or isomeric excited states (heaviest proton emitter ^{185}Bi (isomeric state), the heaviest gs emitter: ^{177}Tl

β-delayed charged particle emission (βp, β2p, for heavier nuclei $\beta\alpha$, $\beta\alpha$p) – 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)

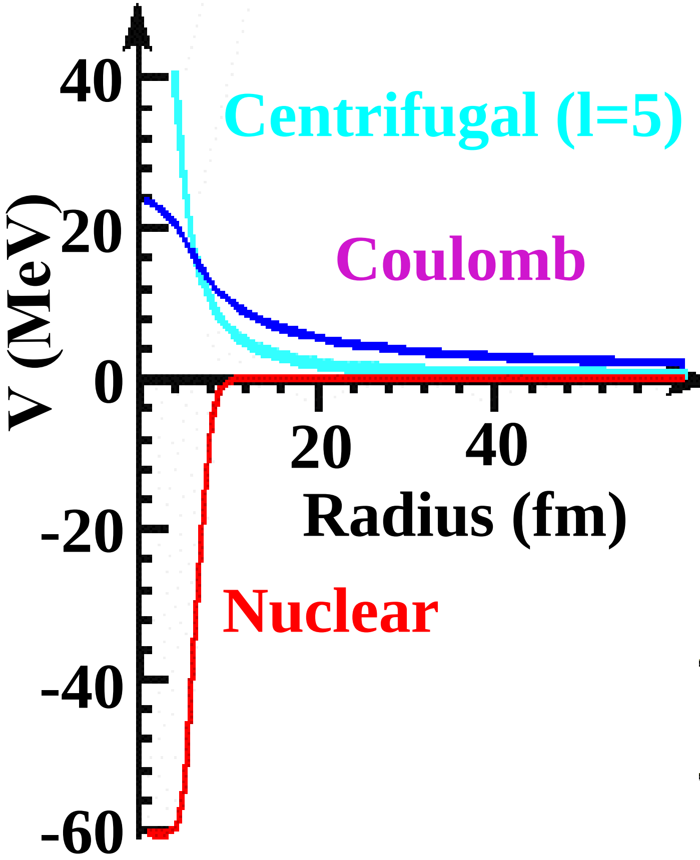
Where is the proton dripline?

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



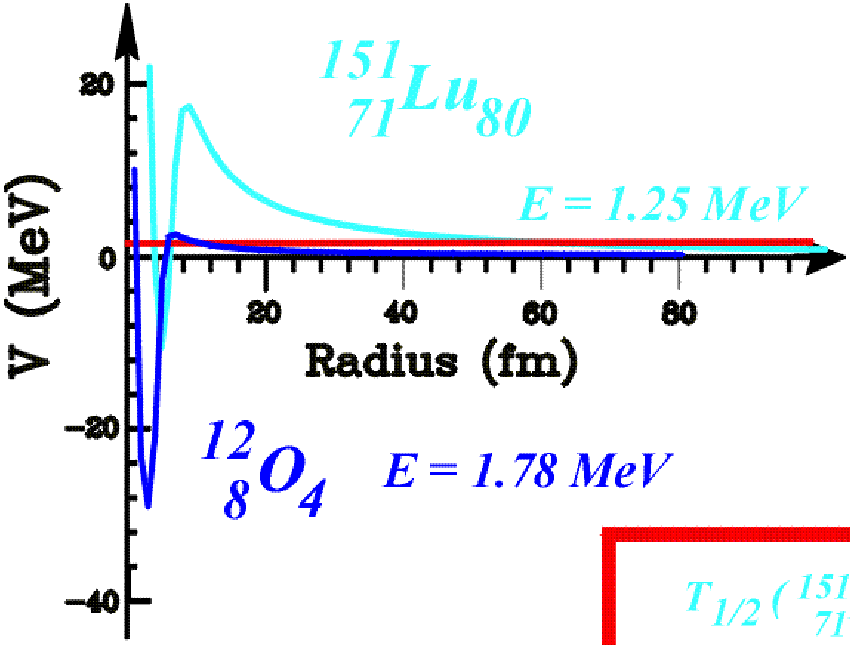
M. Thoennessen, Rep. Prog. Phys. 67 1187 (2004)

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

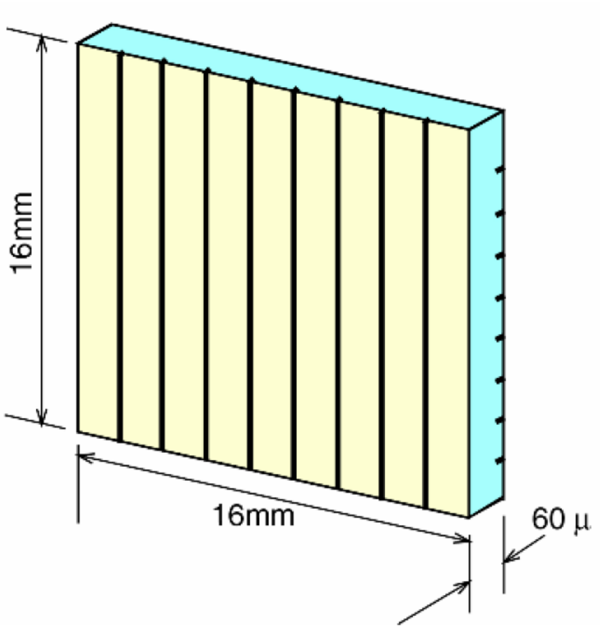


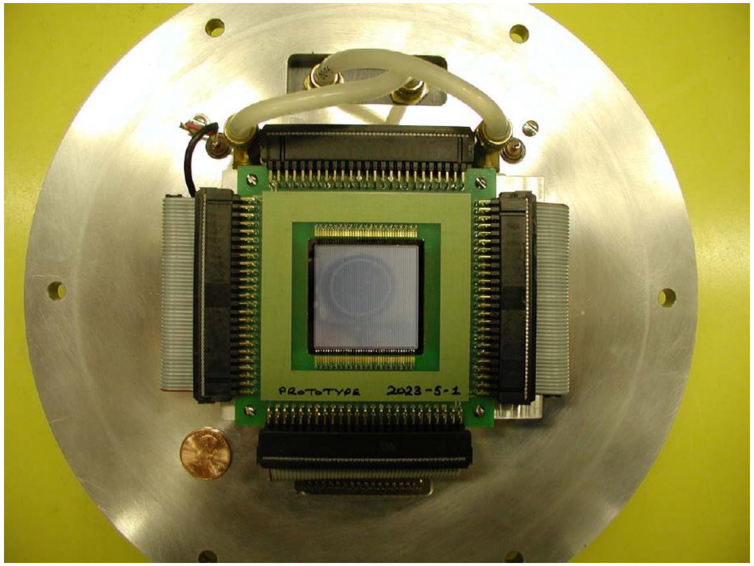
$T_{1/2}(^{151}_{71}Lu_{80}) = 81ms$

$T_{1/2}(^{12}_{8}O_4) \sim 10^{-21} s$

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)

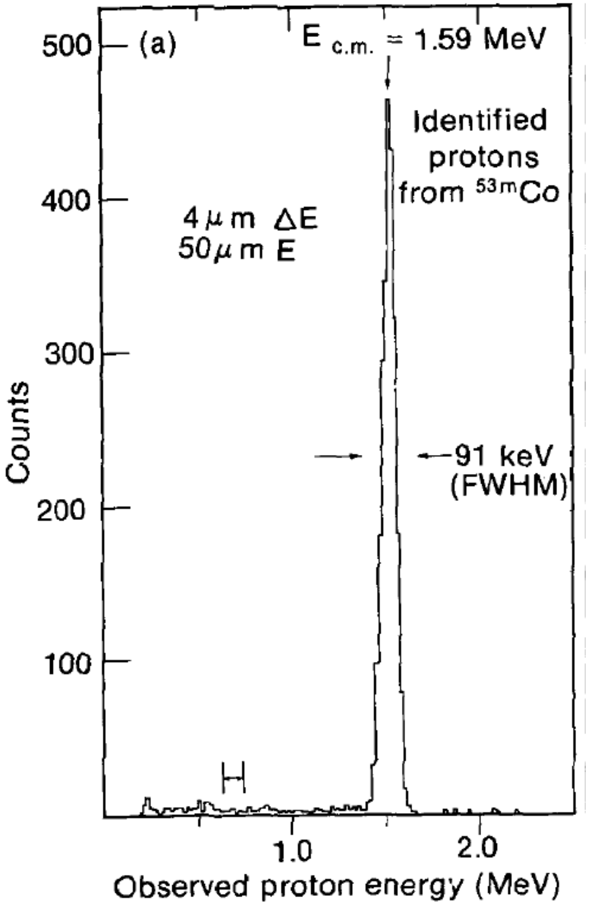


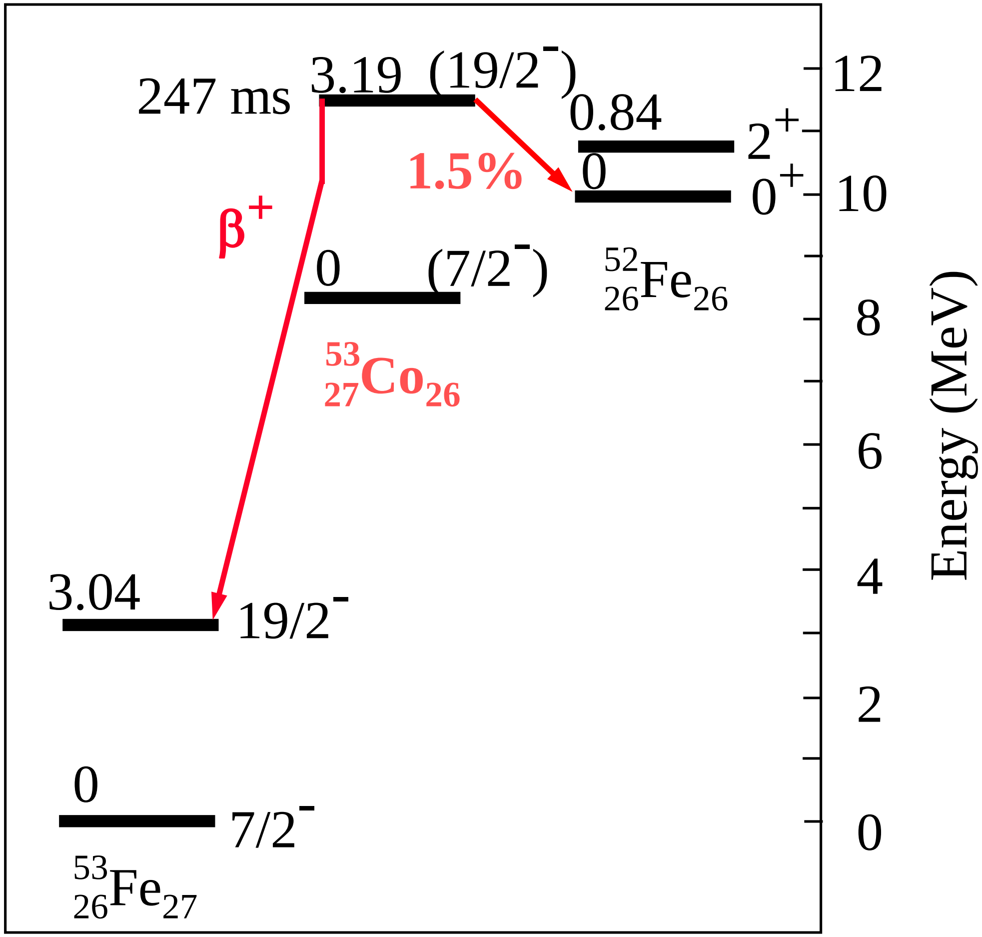


Adapted from C. N. Davids

First Proton Radioactivity
1970

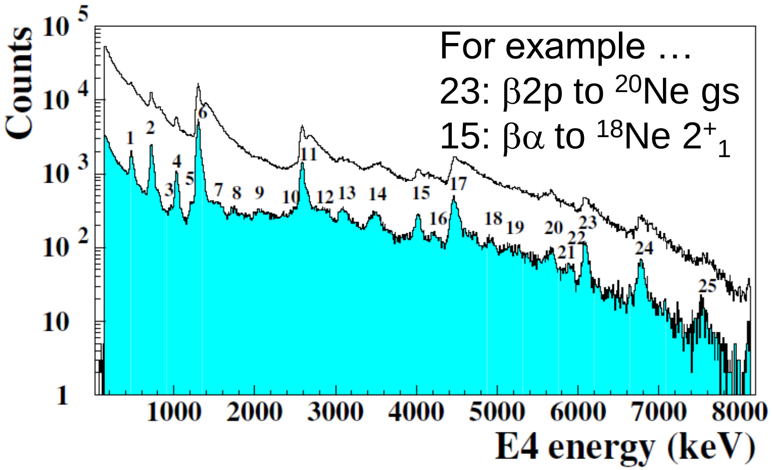
^{53}Co produced in ^{54}Fe(p,2n)



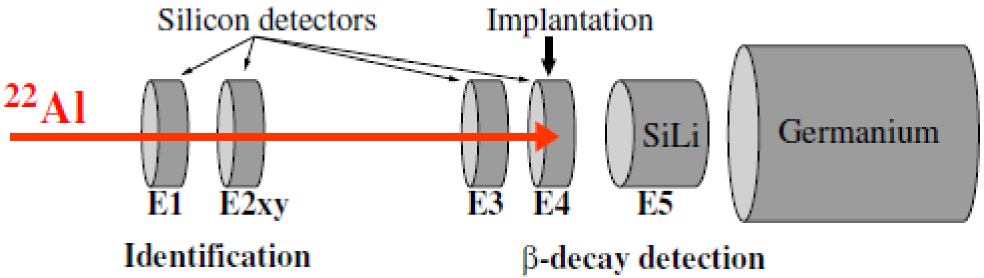


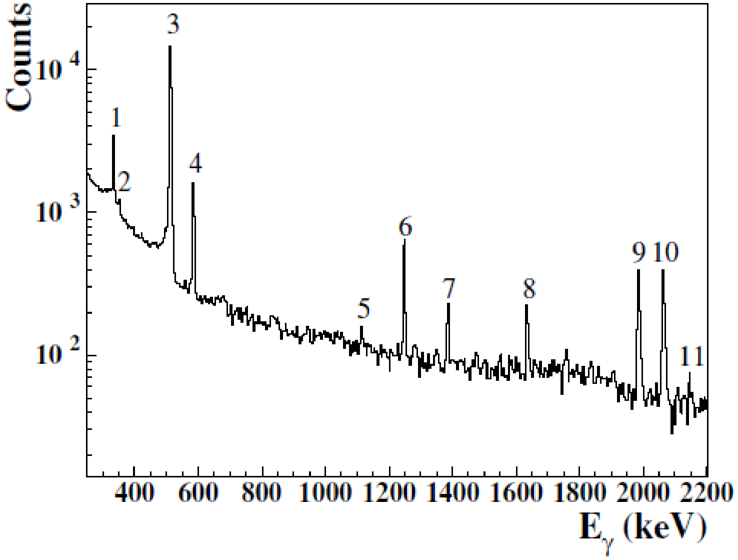
J. Cerny and J. C. Hardy, Annu. Rev. Nucl. Part. Sci. 27, 333 (1977)

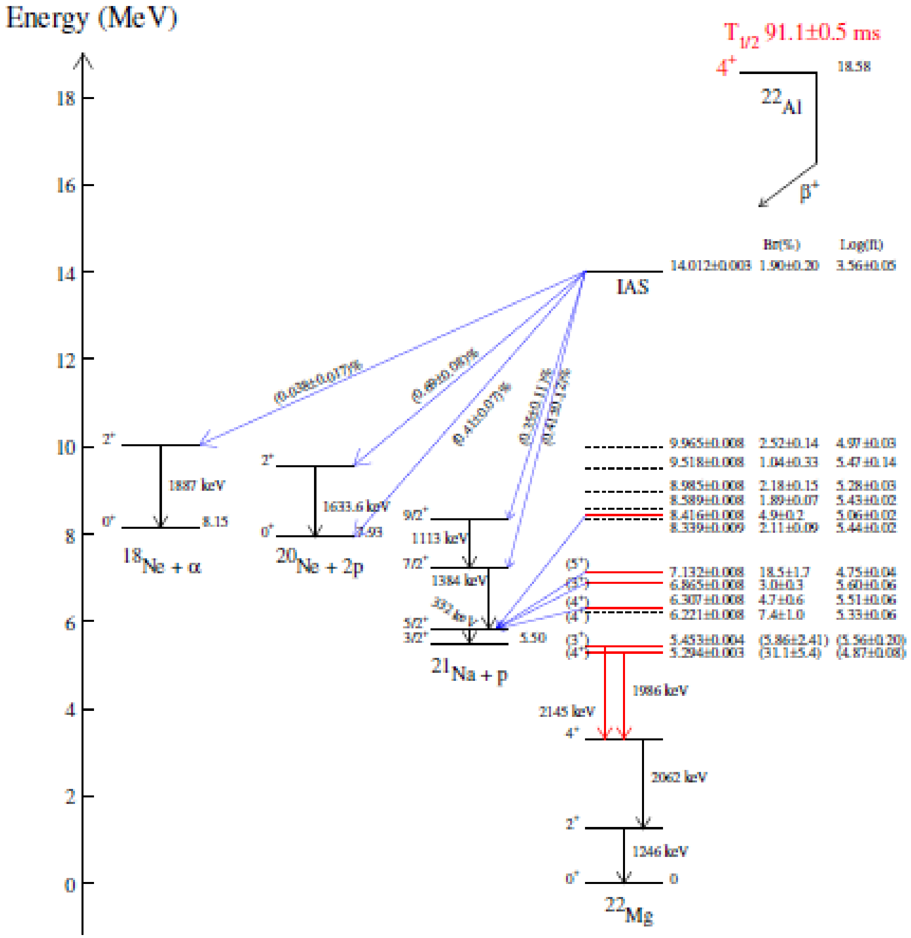
β-delayed proton emitters
The decay of ^{22}Al



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







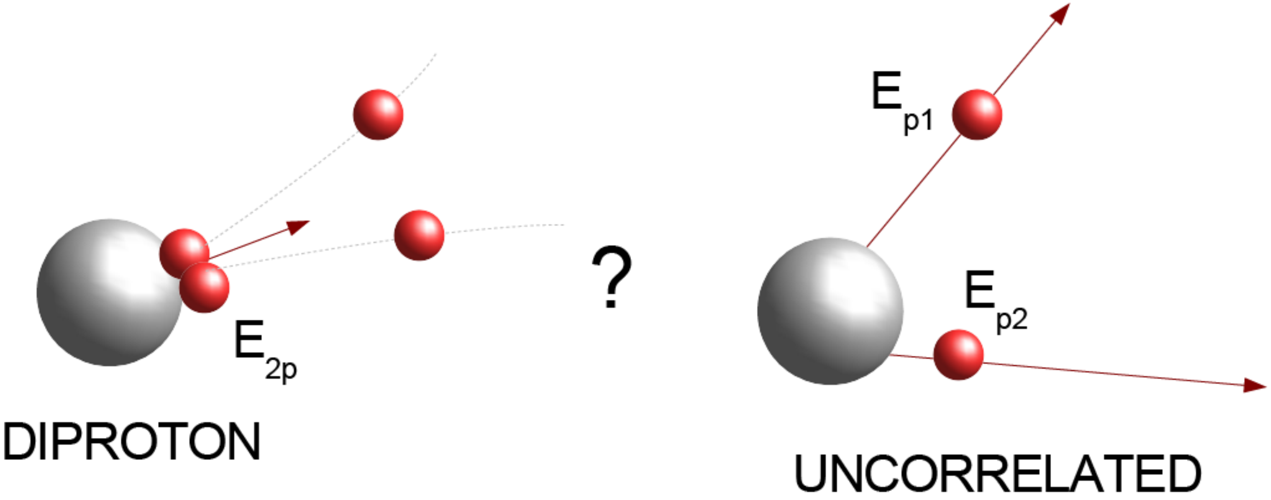
^{22}Al produced in the fragmentation of 95 MeV/u ^{36}Ar at GANIL(LISE3)

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

Two-proton radioactivity

- Predicted by Goldanskii in 1960
- Discovered not too long a ago 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)

Measure the correlations between emitted protons.



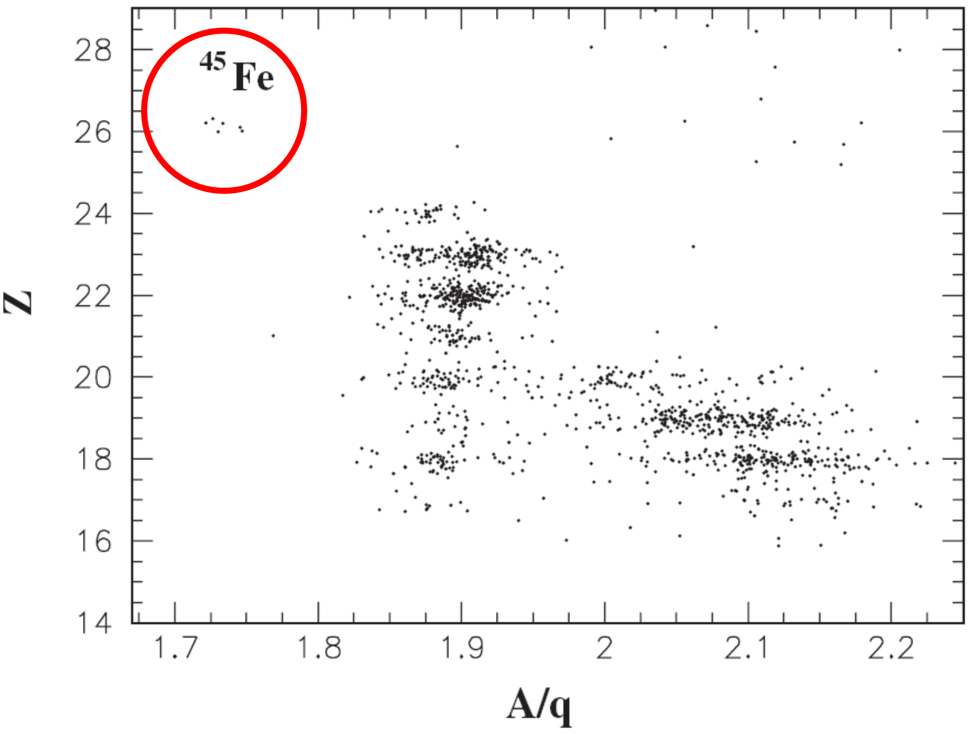
Adapted from R. Grzywacz

Two-proton radioactivity
Predictions

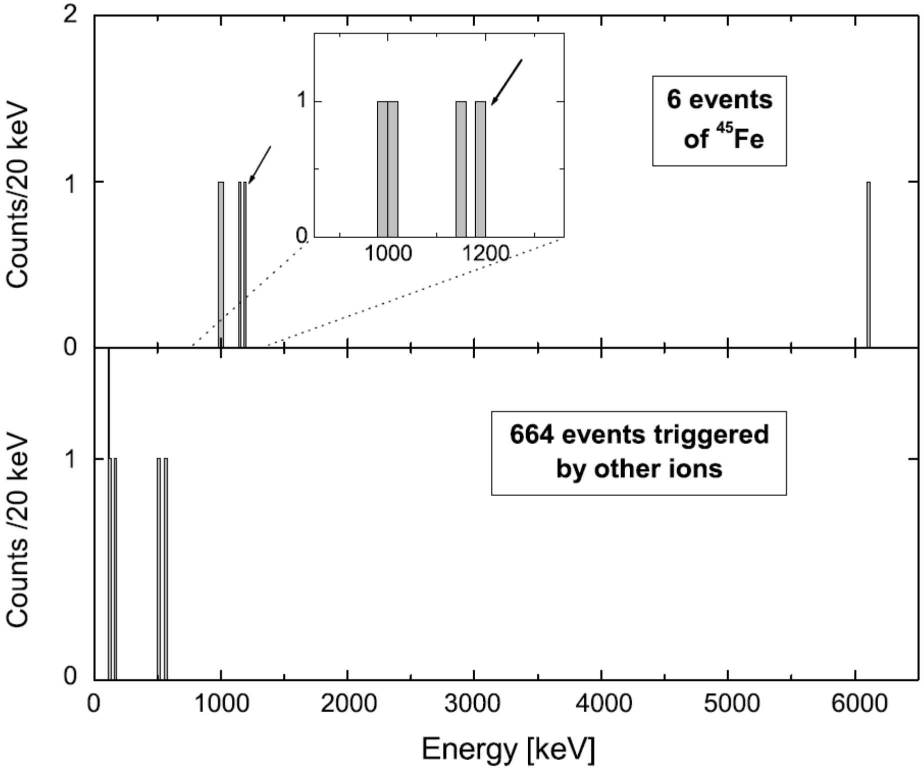
^{38}Ti	$(0.4\text{-}2.3)\text{x}10^{-12}$ ms
^{39}Ti	0.4-2000 ms
^{45}Fe	$10^{-5}\text{-}10^{-1}$ ms
^{48}Ni	0.01-3660 ms
^{63}Se	0.3-5000 ms

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

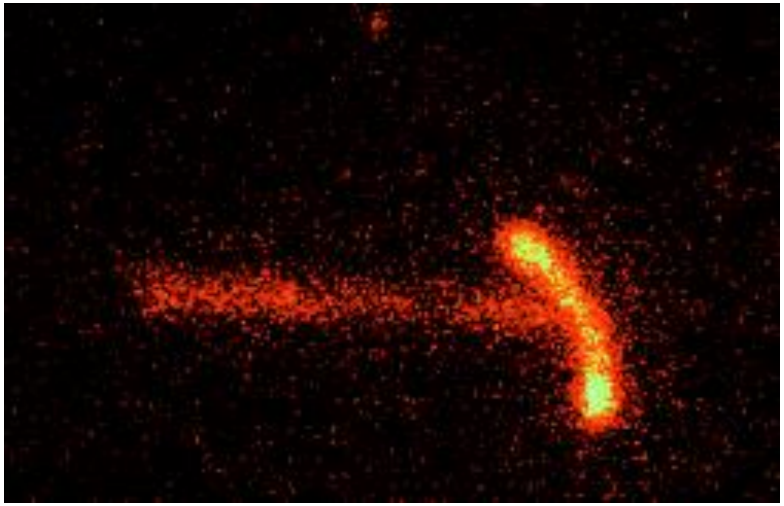


^{45}Fe produced in the fragmentation of ^{58}Ni at 650 MeV/u.

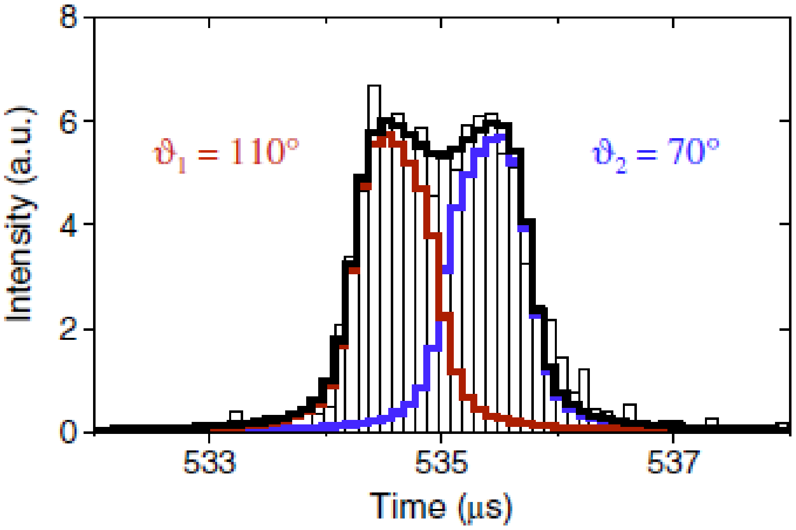
M. Pfützner et al., Eur. Phys. A 14, 279 (2002)

^{45}Fe: 2-proton decay 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



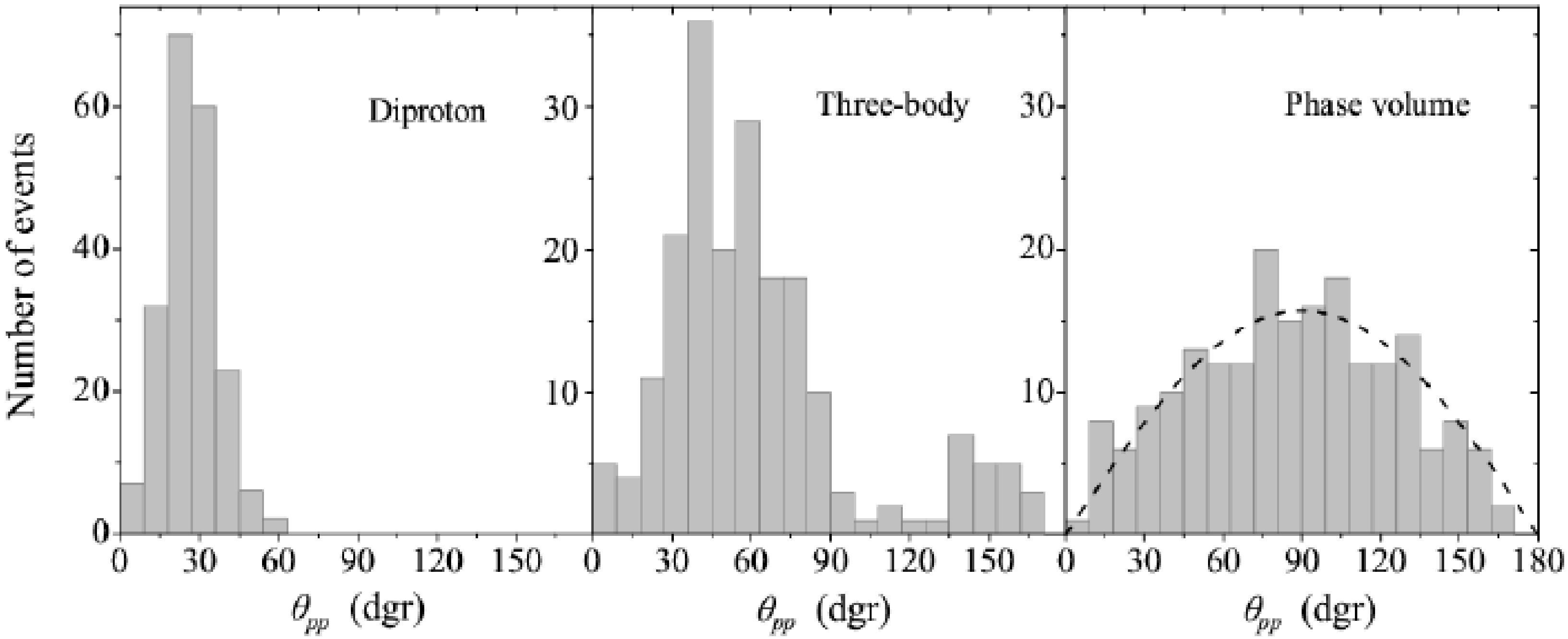
Time profile of the total light intensity measured by photomultiplier tube

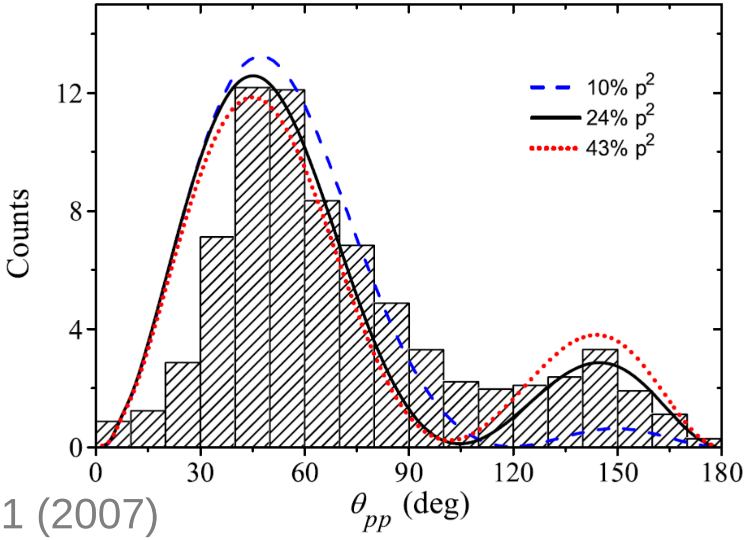
2p radioactivity but no simple ^{2}He (di-proton) picture

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

^{45}Fe: Correlation of the protons?

Pfutzner, Grigorenko et al.

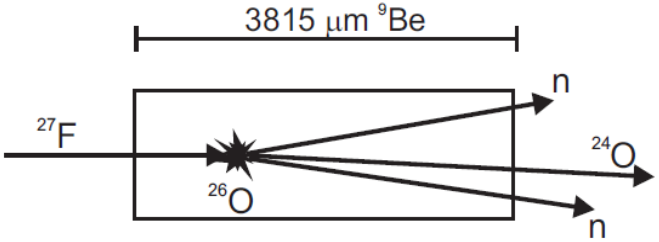




K. Miernik et al., PRL 99, 192501 (2007)

What about 2n: ^{26}O – maybe a case of two-neutron radioactivity

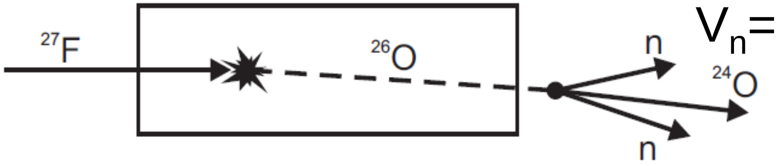
- Lifetime limit for radioactivity is ~10^{-12} s
- New technique developed to measure the lifetime of neutron emitting nuclei: Decay in Target (DiT)



Immediate decay

$V_{rel}=V_n-V_{frag}$

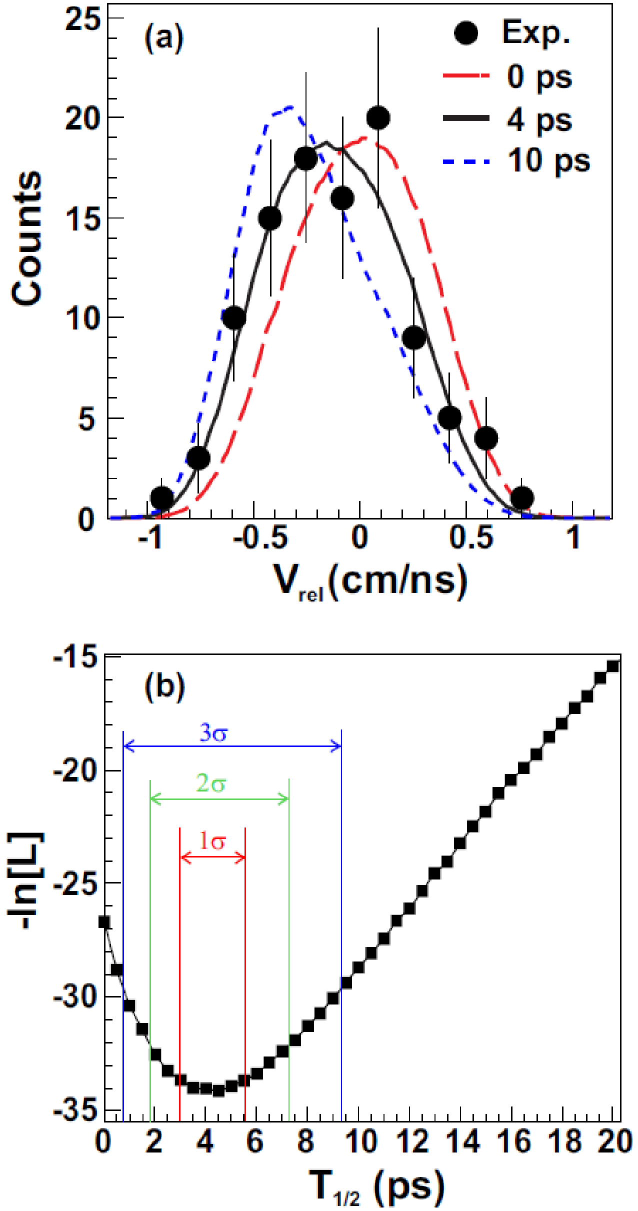
V_n=11.8 cm/ns



V_n=10.9 cm/ns

“Long” lifetime = slow neutrons

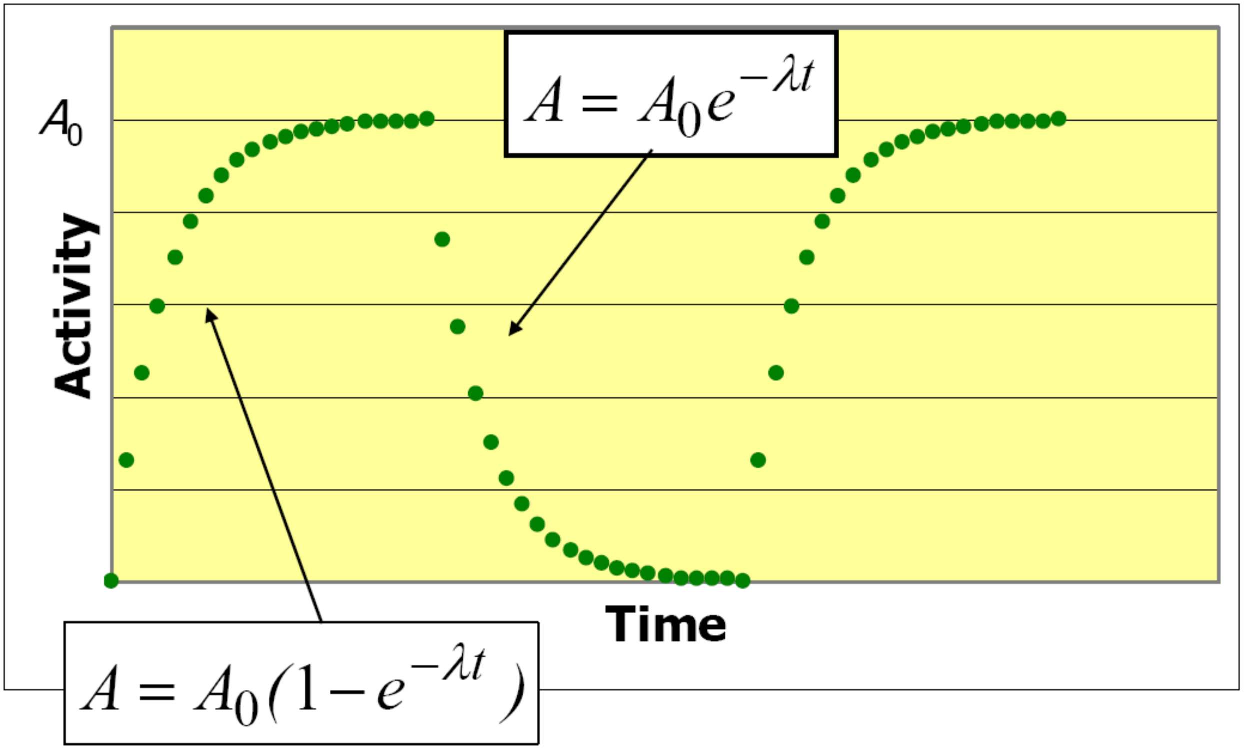
Lifetime of two-neutron decay of ^{26}O measured to be $T_{1/2}$ = 4.5 ± 1.5 (*stat.*) ± 3 (*sys.*) ps



Z. Kohley et al. PRL 110, 152501 (2013)

Half-lives

Bulk activity measurements



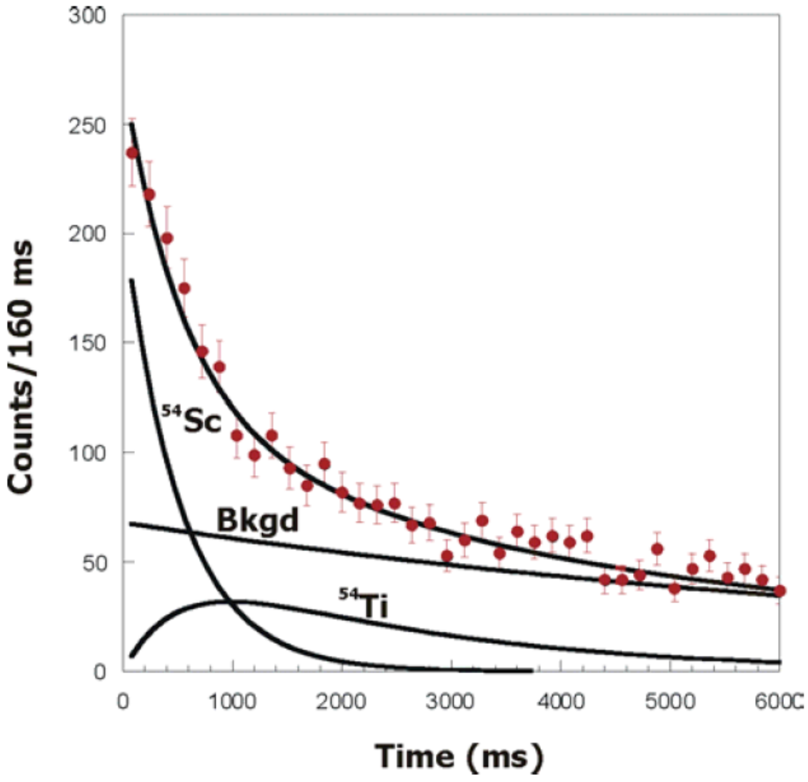
$\lambda = \ln 2 / t_{1/2}$

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

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

$\downarrow$ $T_{1/2}$ = 360±60 ms

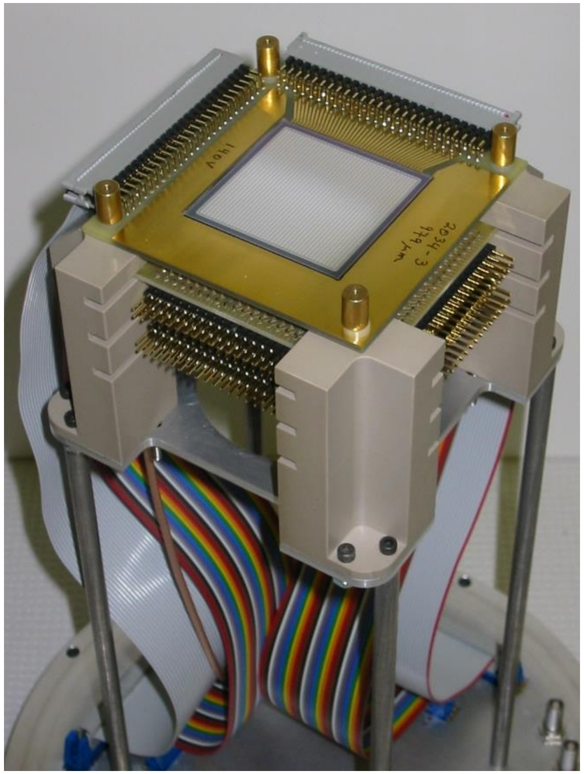
^{54}Ti

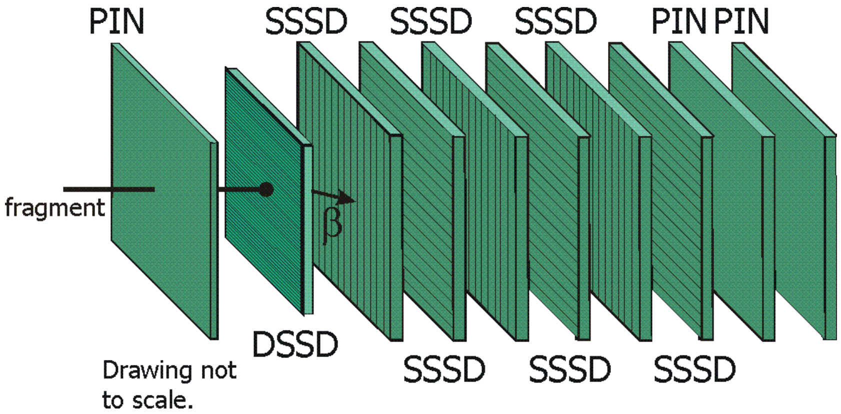
- **Reduced background from in-flight tracking and identification of individual isotopes in the beam on a particle-by-particle basis**

Adapted from P. F. Mantica

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

Beta counting systems
Example: BCS at NSCL





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

Adapted from P. F. Mantica

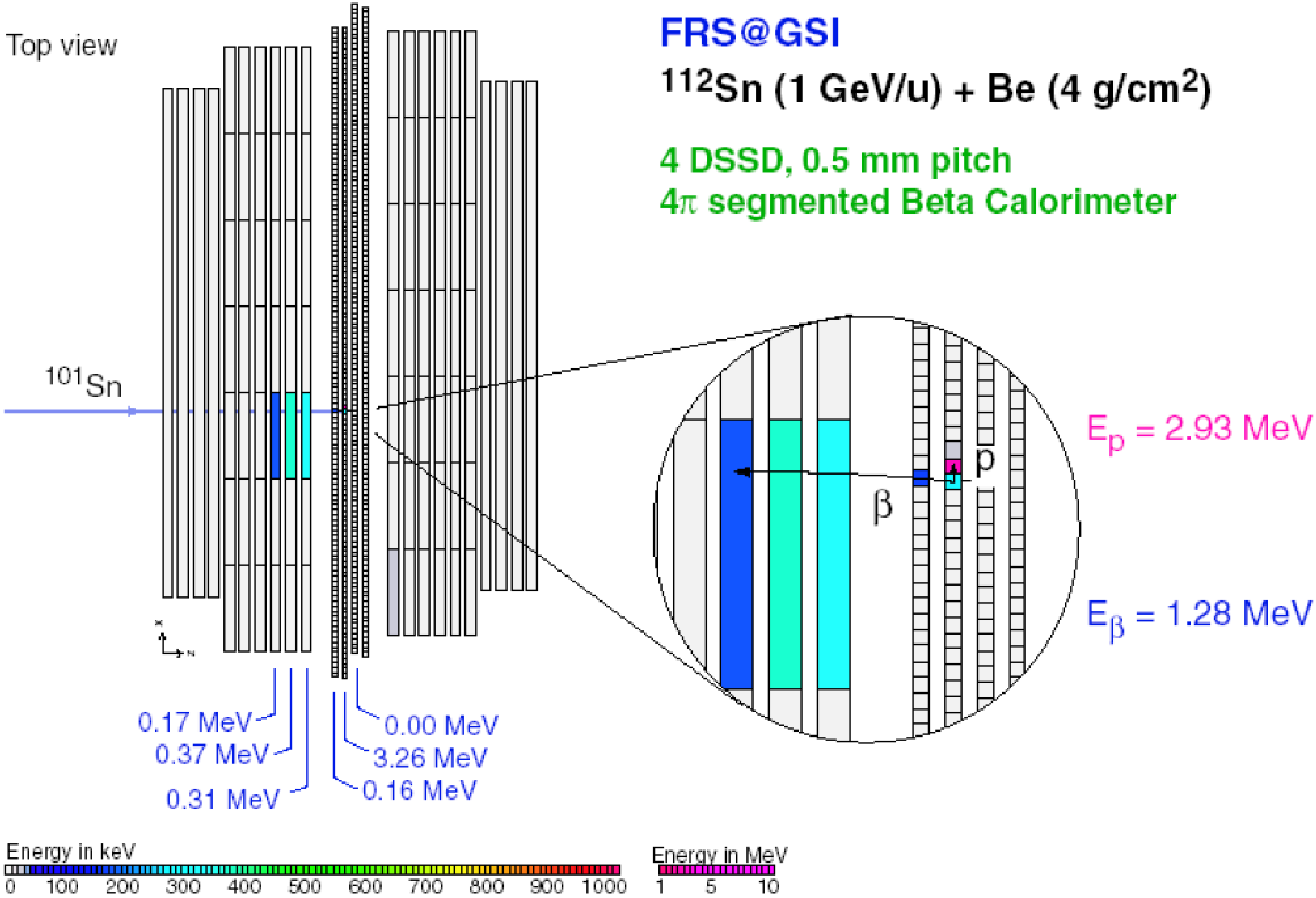
^{101}Sn β-decay

FRS@GSI

^{112}Sn (1 GeV/u) + Be (4 g/cm^2)

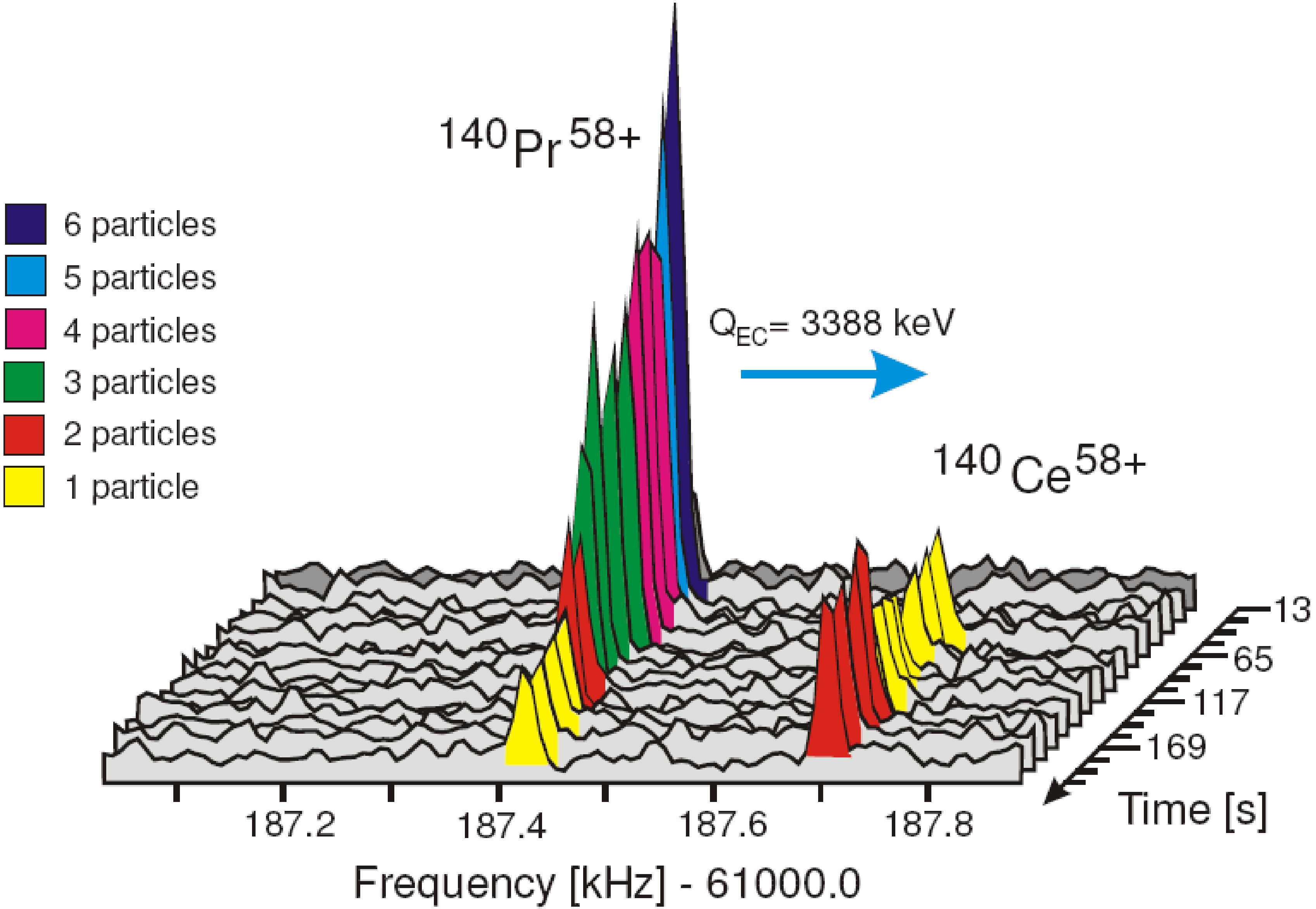
4 DSSD, 0.5 mm pitch

4π segmented Beta Calorimeter



A. Stolz (2003)

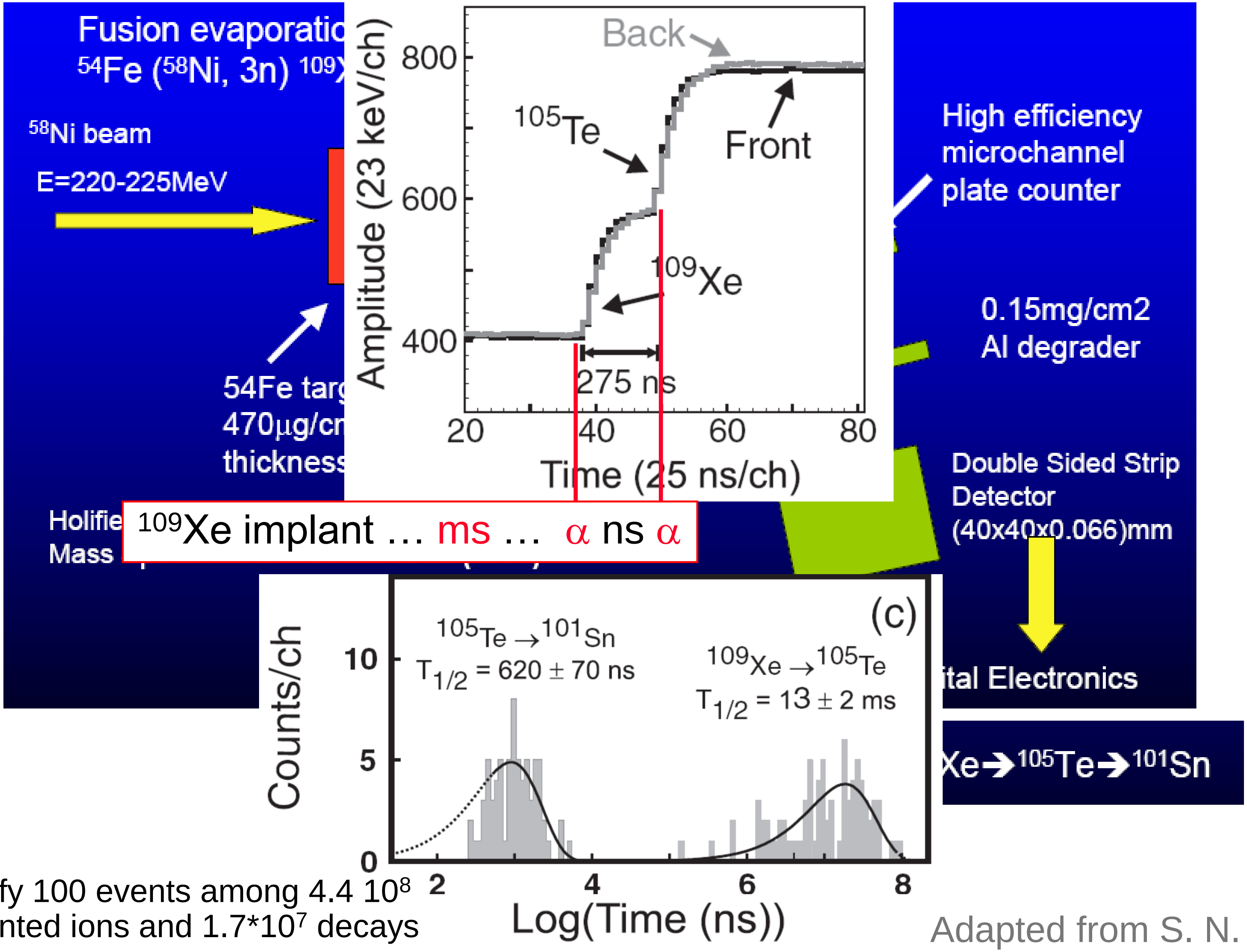
Caught in the act: ^{140}Pr → ^{140}Ce β-decay in the ESR@GSI



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

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

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

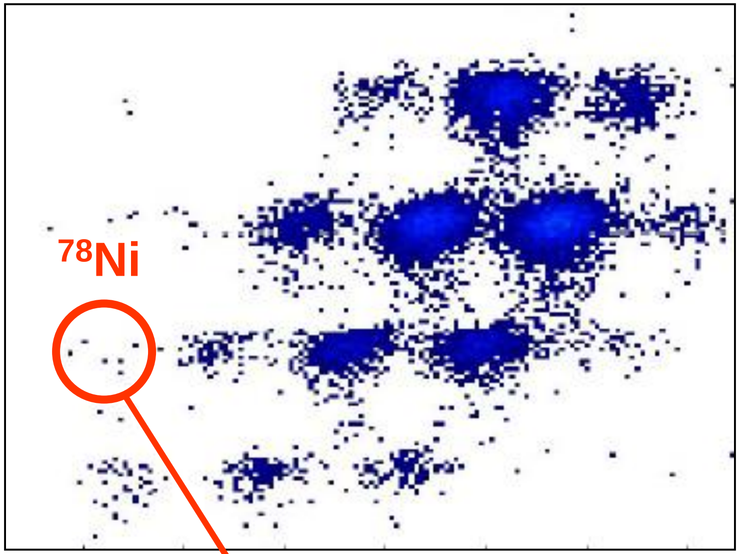


identify 100 events among 4.4 10^8 implanted ions and $1.7*10^7$ decays

Adapted from S. N. Liddick

Doubly magic nucleus accelerates synthesis of heavy elements

Particle identification in rare-isotope beam from NSCL at Michigan State University

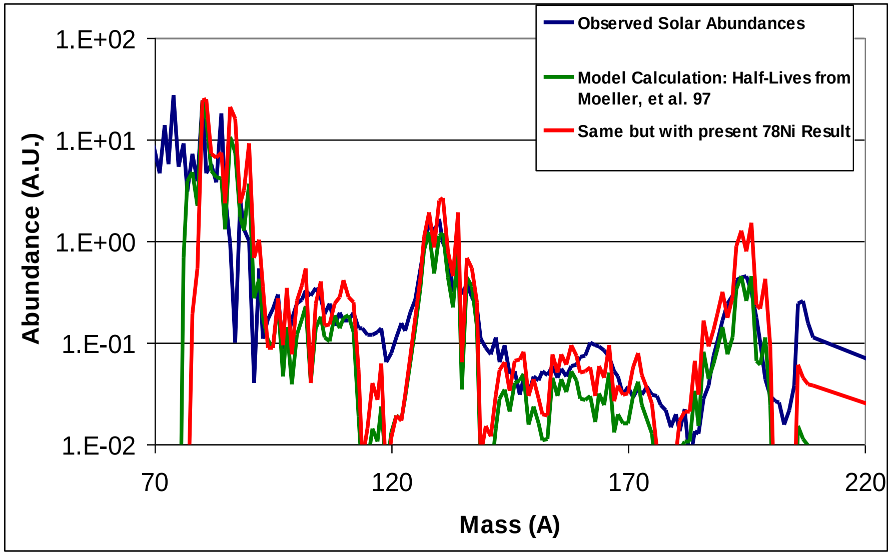


Measured half-life of ^{78}Ni with 11 events This is the most neutron rich of the 10 possible classical doubly-magic nuclei in nature.

Result: 110 $^{+100}_{-60}$ ms

P. Hosmer et al. PRL 94, 112501 (2005)

Model calculation for synthesis of heavy elements during the r-process in supernova explosions



Models produce excess of heavy elements with new shorter ^{78}Ni half-life

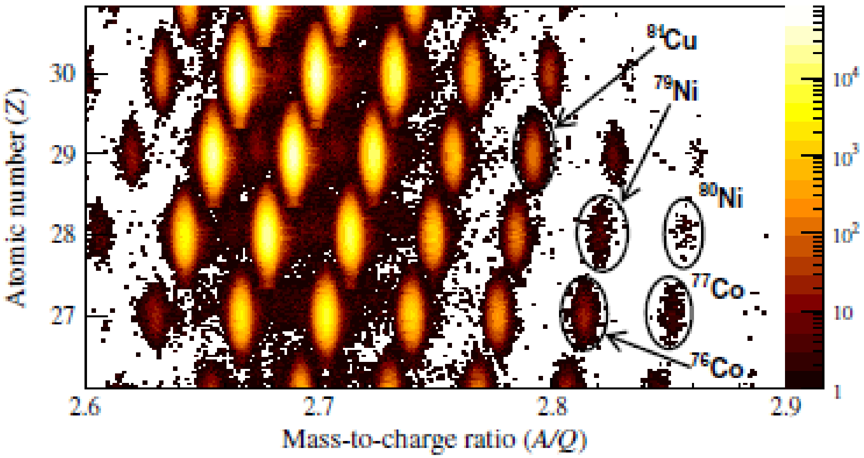
→ the synthesis of heavy elements in nature proceeds faster than previously assumed

… a step in the quest to find the origin of the heavy elements in the cosmos

Adapted from H. Schatz

10 years and a new facility later … at RIBF in RIKEN

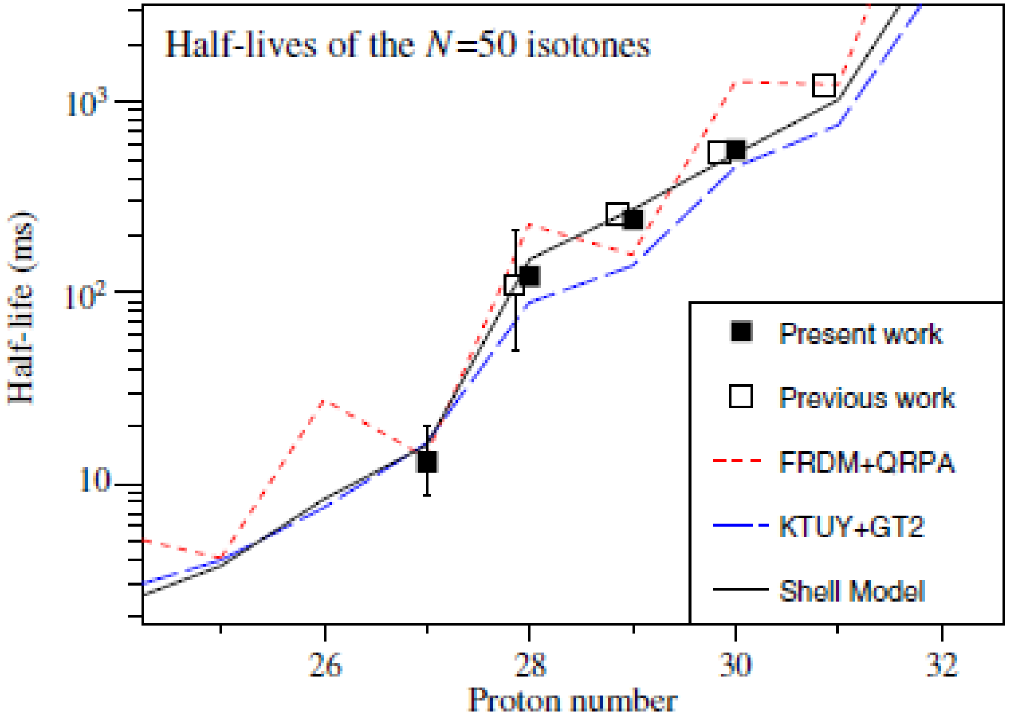
Particle identification in rare-isotope beam from RIBF at RIKEN



Very similar experimental scheme

- Produced by in-flight fission of ^{238}U
- Implantation into Si stack

Significantly reduced uncertainty in the half-life of ^{78}Ni and new results for more neutron-rich N=50 isotones



Astrophysical conclusions unchanged

Z. Y. Xu et al. PRL 113, 032505 (2014)

Take away

- Implementation of experiments can influence the discovery potential
- Experimenters need to be explicit about assumptions and model dependencies
- Examples of techniques to explore ground-state properties of exotic nuclei
  - Existence of a rare isotope – one of the most basic benchmarks for theory, very challenging experiments
  - Interesting exotica occur at the driplines
  - Nuclear masses (G. Savard's lecture) – important for many thing, including nuclear structure, astrophysics and fundamental symmetries
  - Ground-state halflives – have a challengingly large range that requires experiments to adapt, important for nuclear structure, astrophysics and fundamental symmetries