Nuclear Structure Experiments I

Thursday

before lunch

Preliminaries

Nuclear existence

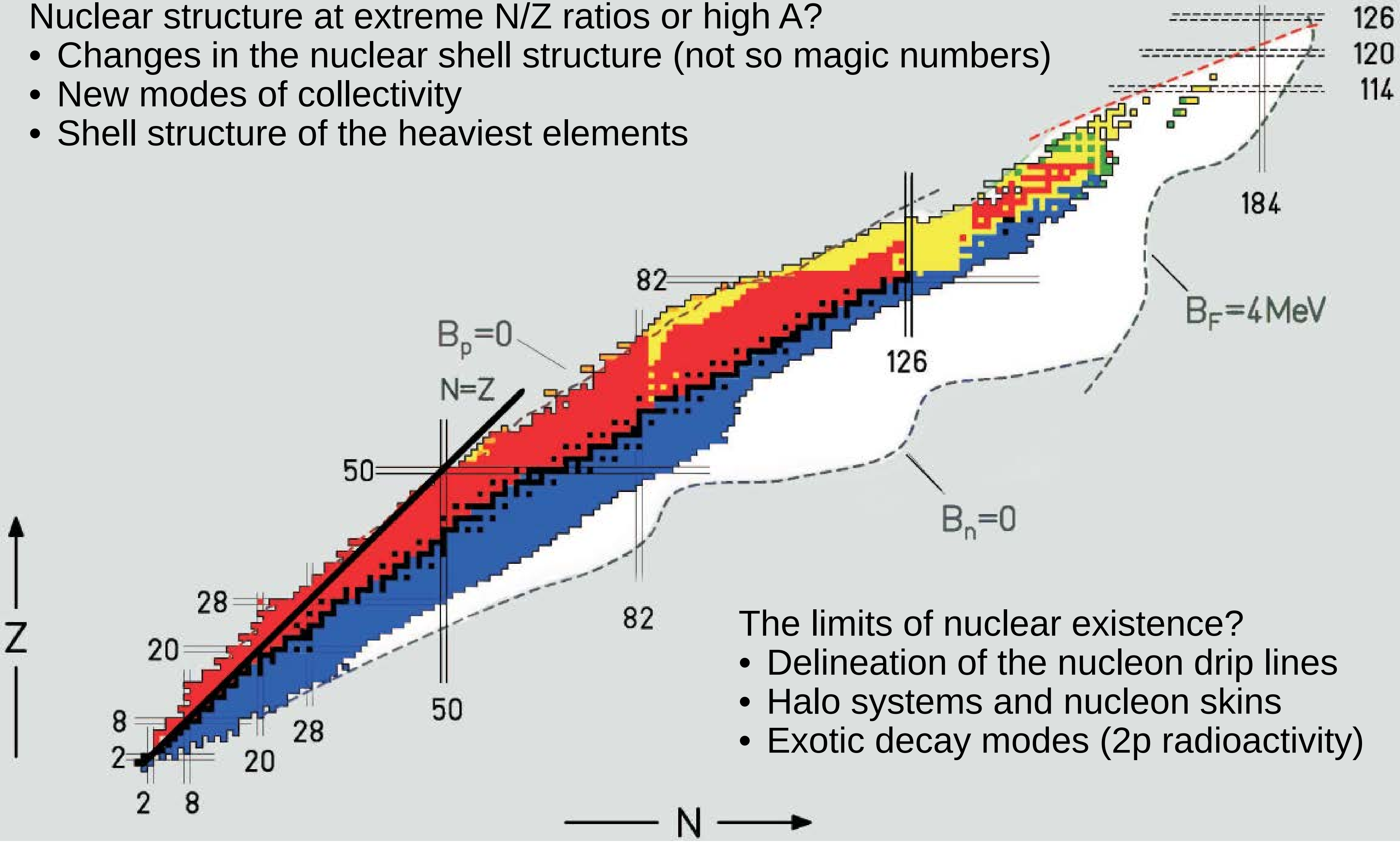
Masses

Ground-state half-lives

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

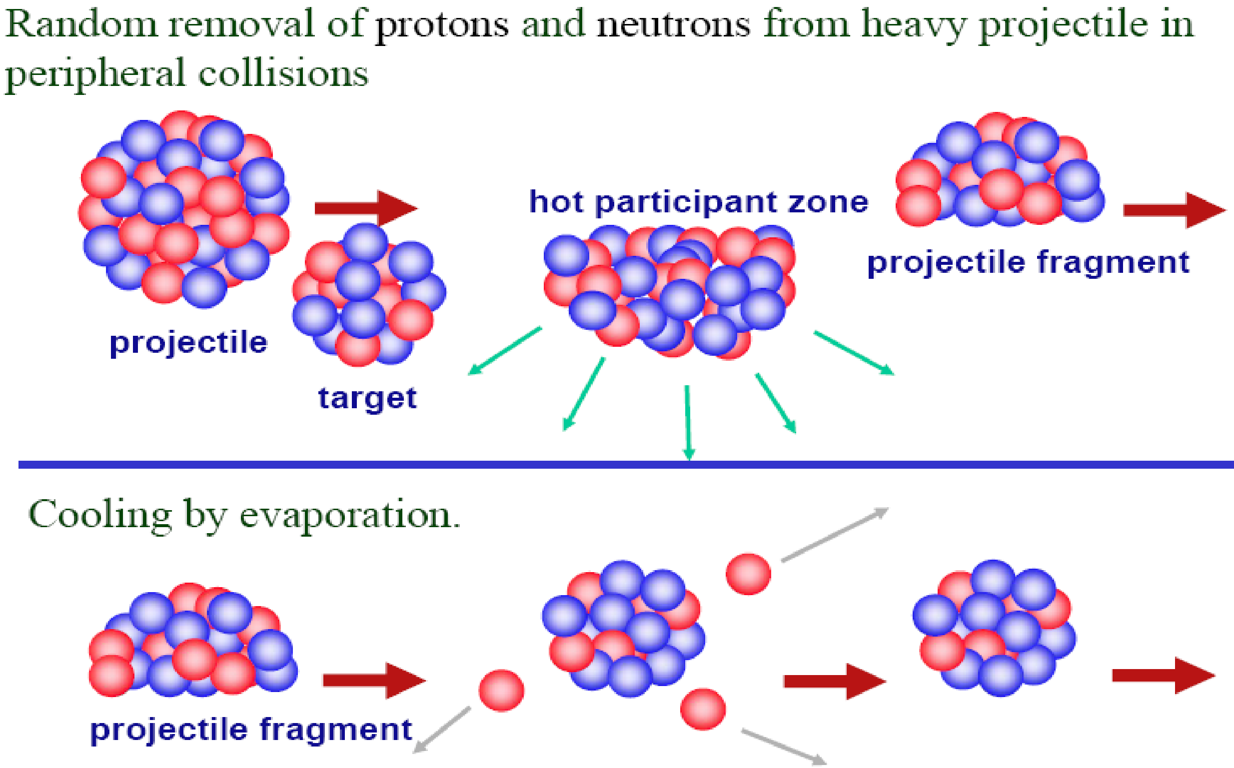
Preliminaries (3)

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

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)

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

Location of the driplines

Experimental task: How to find a needle in a haystack

How many neutrons can a proton bind?

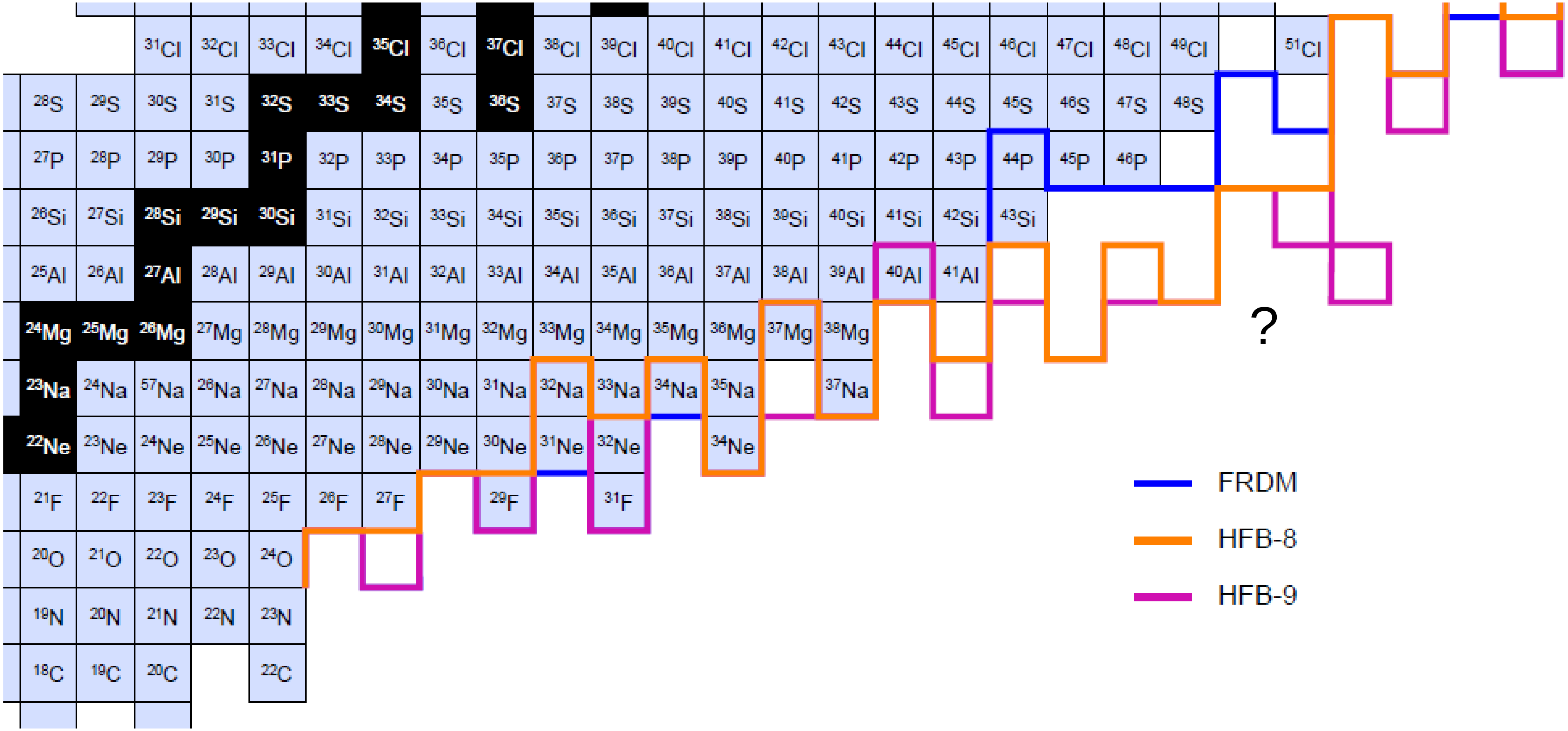
The limit of nuclear existence is characterized by
the nucleon driplines

- 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.“

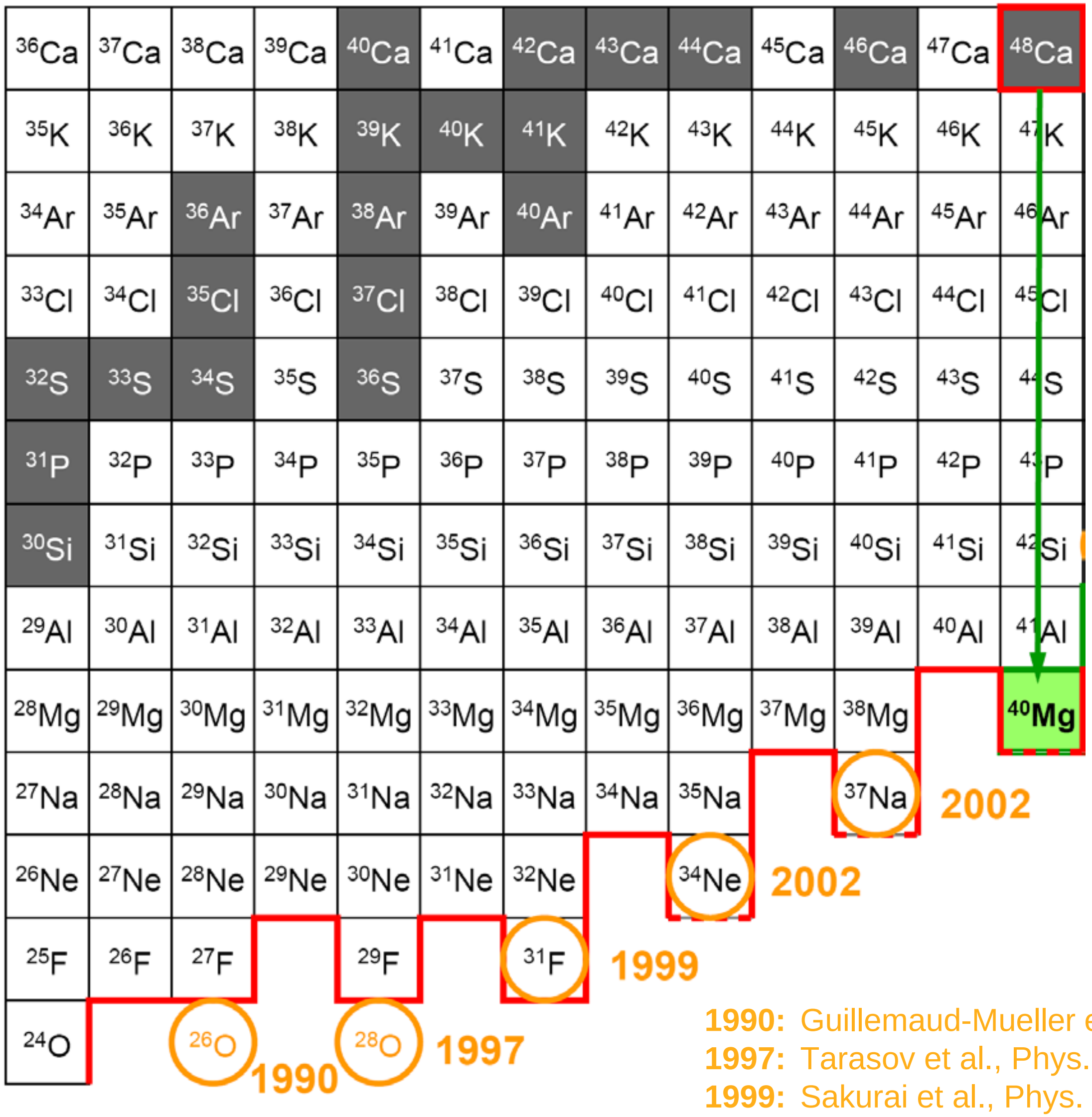
- P. G. Hansen & J. A. Tostevin: "(the dripline is) where the nucleon separation energy goes to zero."

Where is the neutron dripline?

Predictive power, anybody?

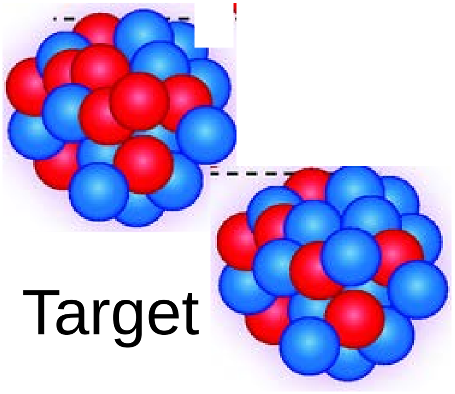


Dripline history and a plan …



^{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)

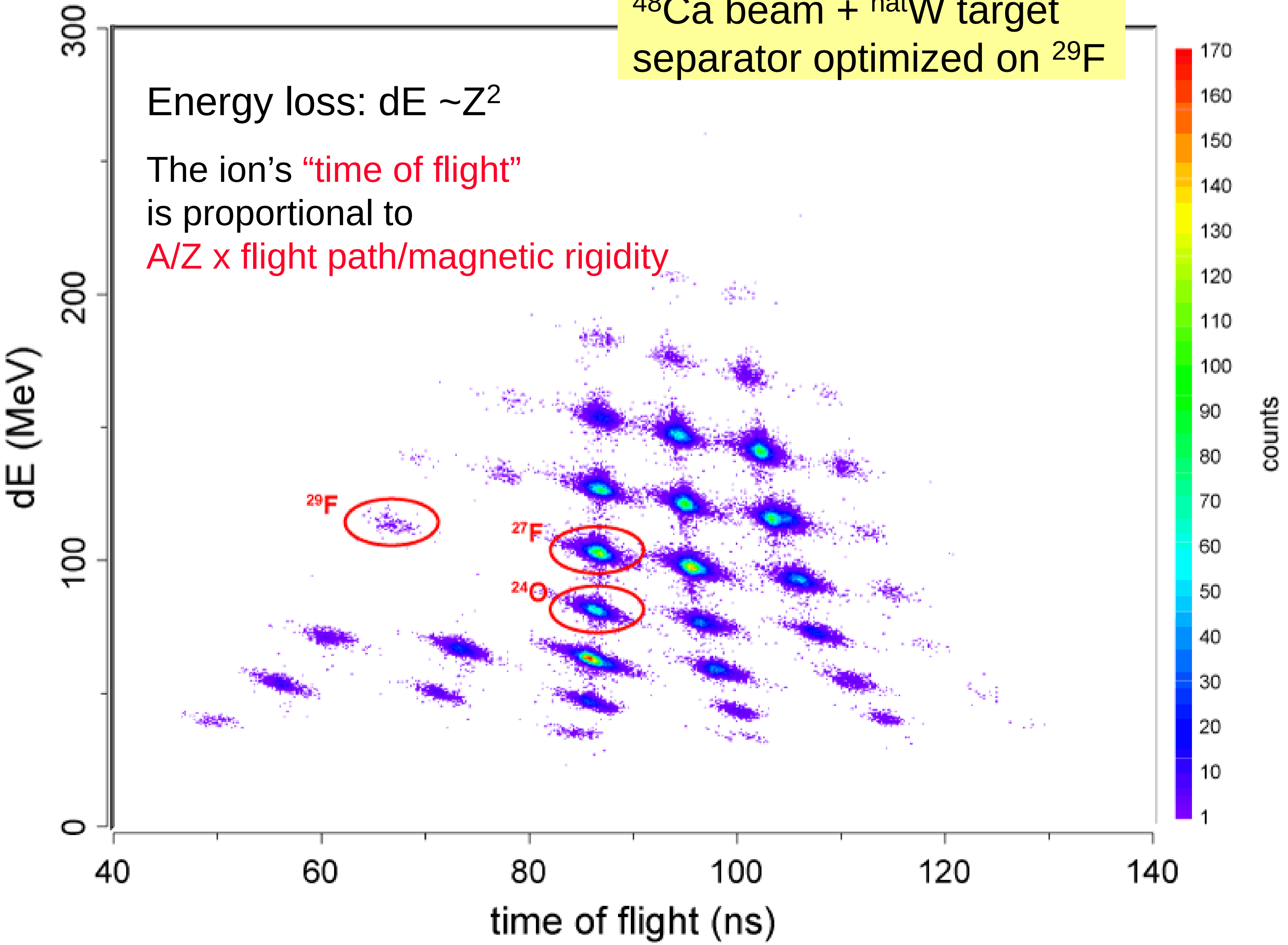


Target

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!



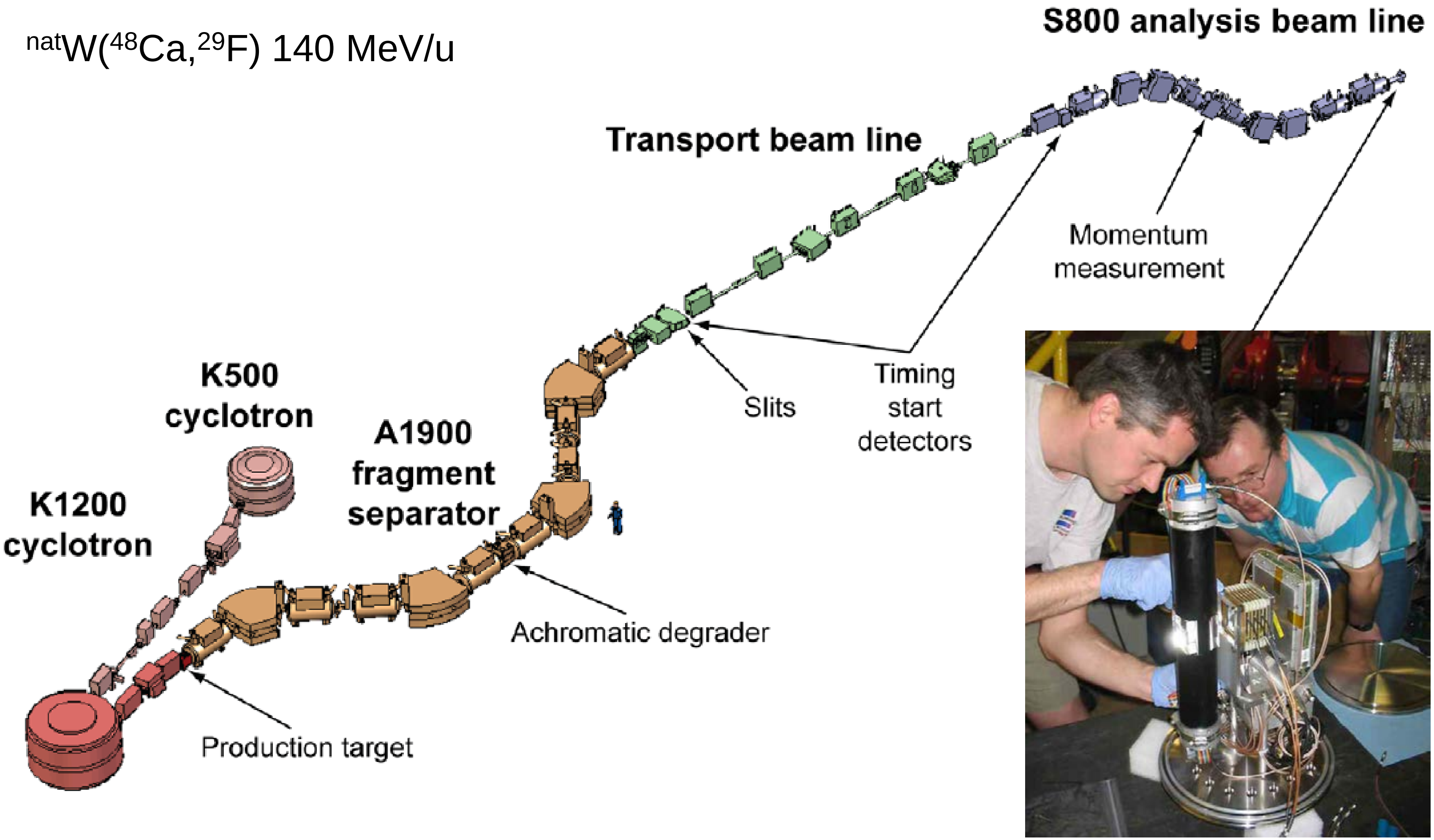
^{48}Ca beam + ^{nat}W target
separator optimized on ^{29}F

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?

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



S800 analysis beam line

Transport beam line

Momentum measurement

Timing start detectors

Slits

K500 cyclotron

A1900 fragment separator

K1200 cyclotron

Achromatic degrader

Production target

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

^{40}Mg and more!

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

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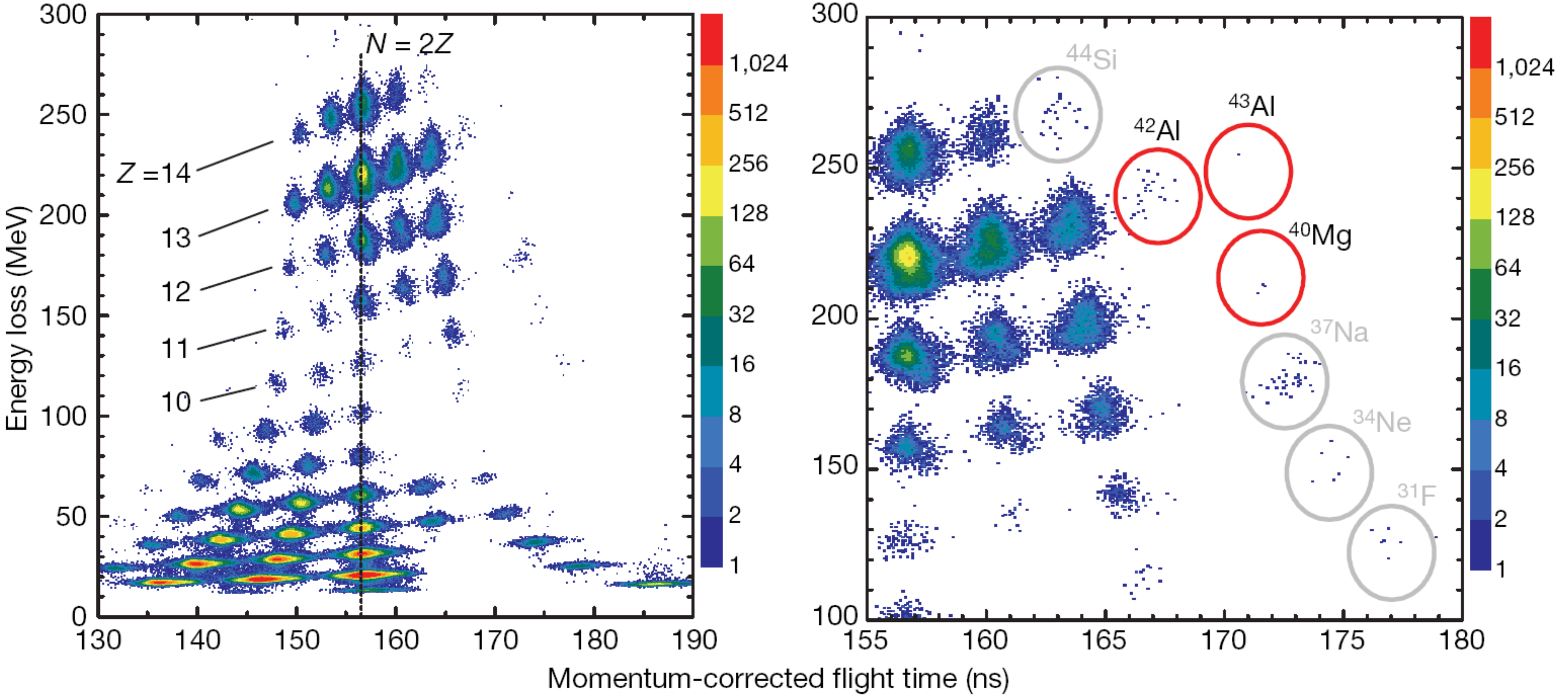


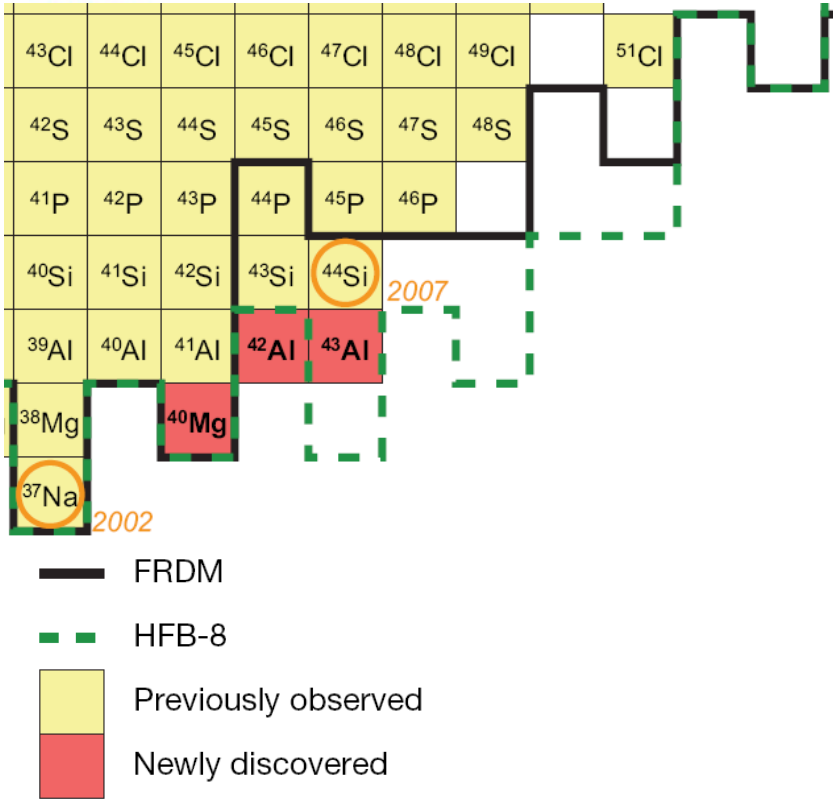
Data taking: 7.6 days at 5 x10^{11} particles/second

3 events of ^{40}Mg

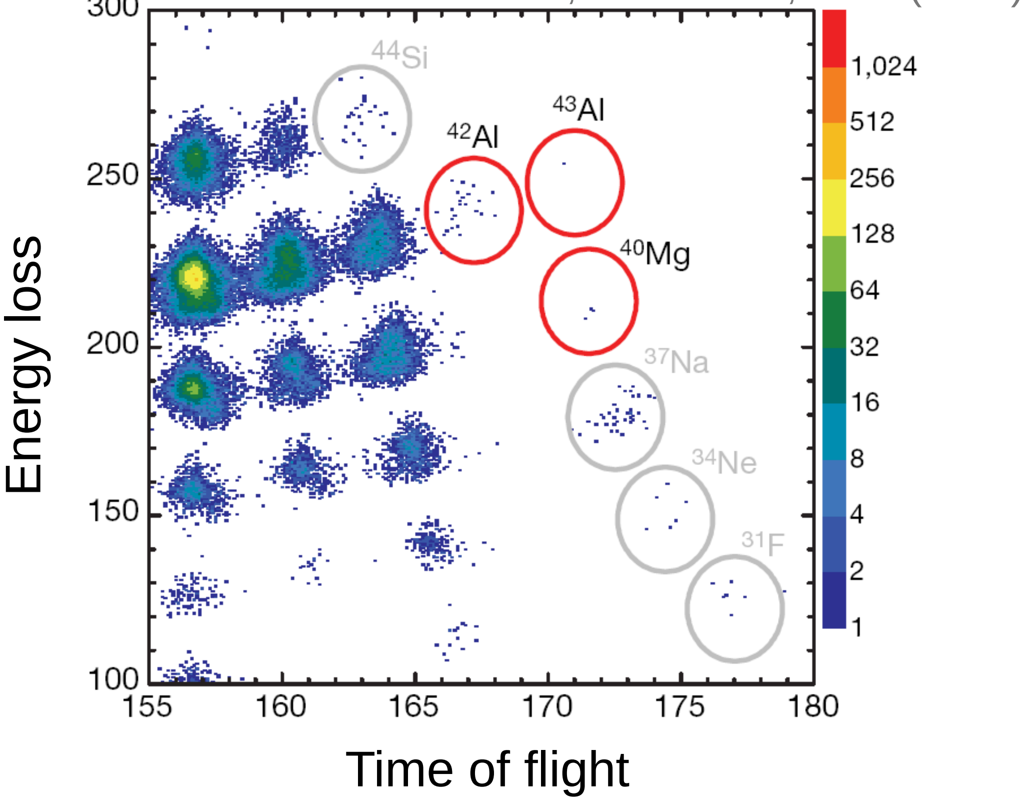
23 events of ^{42}Al

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

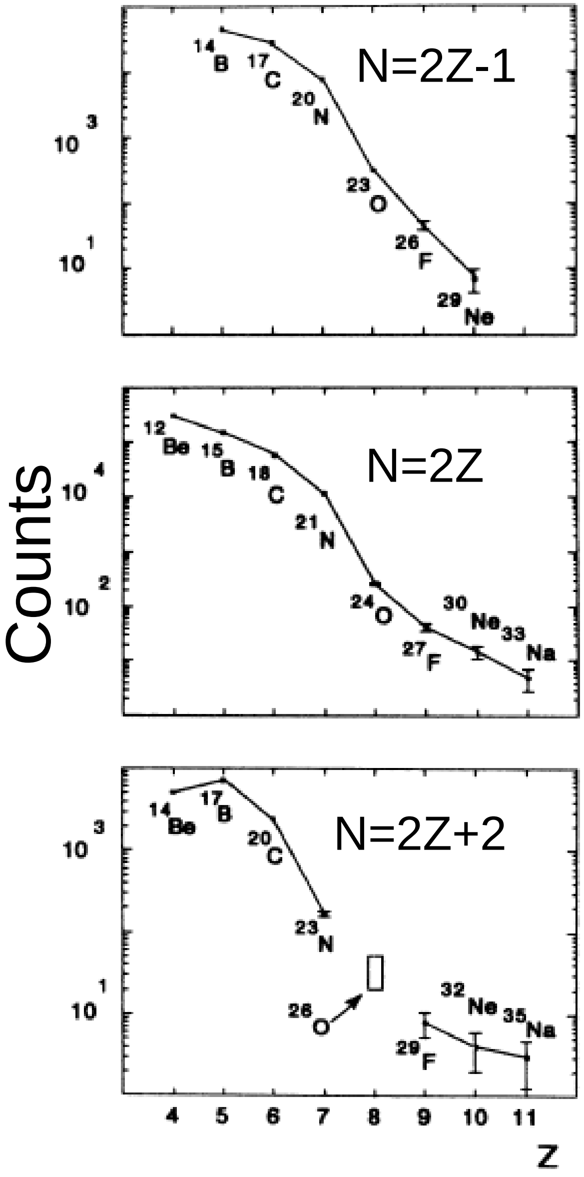
1 event ^{43}Al

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

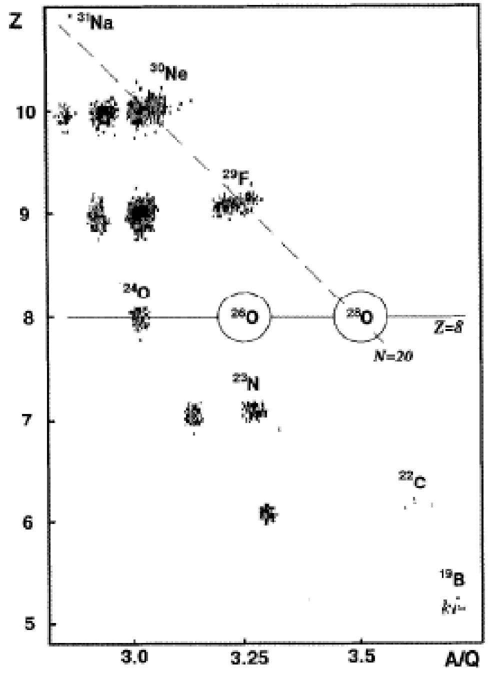
Guillemaud-Mueller et al., PRC 41, 937 (1990)

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

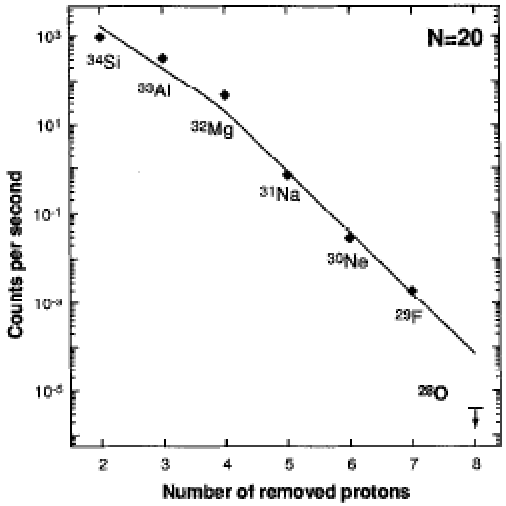


^{48}Ca on Ta
at 44 MeV/u
(GANIL)

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



^{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

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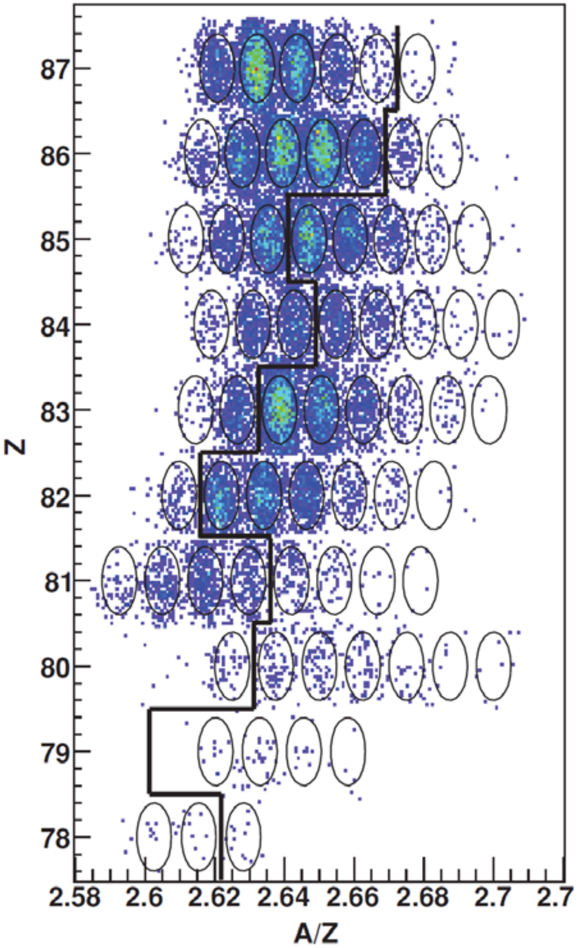
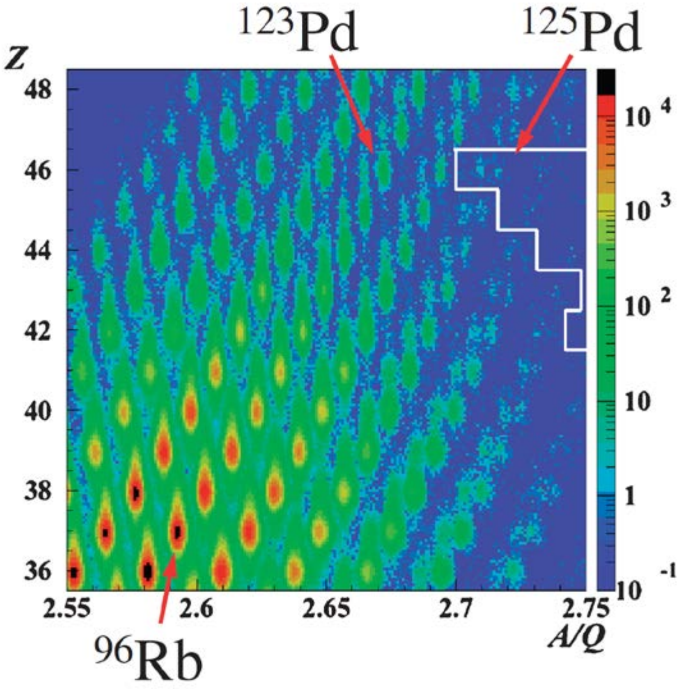
Fragmentation of ^{238}U at GSI



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).

Masses

Indirect

- Decay measurements and kinematics in two-body reactions

reactions:

$A(a,b)B$

$Q = M_A + M_a - M_b - M_B$

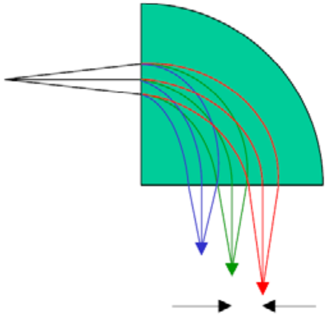
decays:

$B \rightarrow A + b$

$Q_\alpha = M_B - M_A$

Direct

- Conventional mass spectrometry
  - Cern PS, Chalk River
- Time-of-flight
  - spectrometer (SPEG, TOFI, S800)
  - Multi-turn (cyclotrons, storage rings)
- Frequency measurements
  - Penning traps
  - Storage rings



Mass separator (spectrograph, spectrometer)

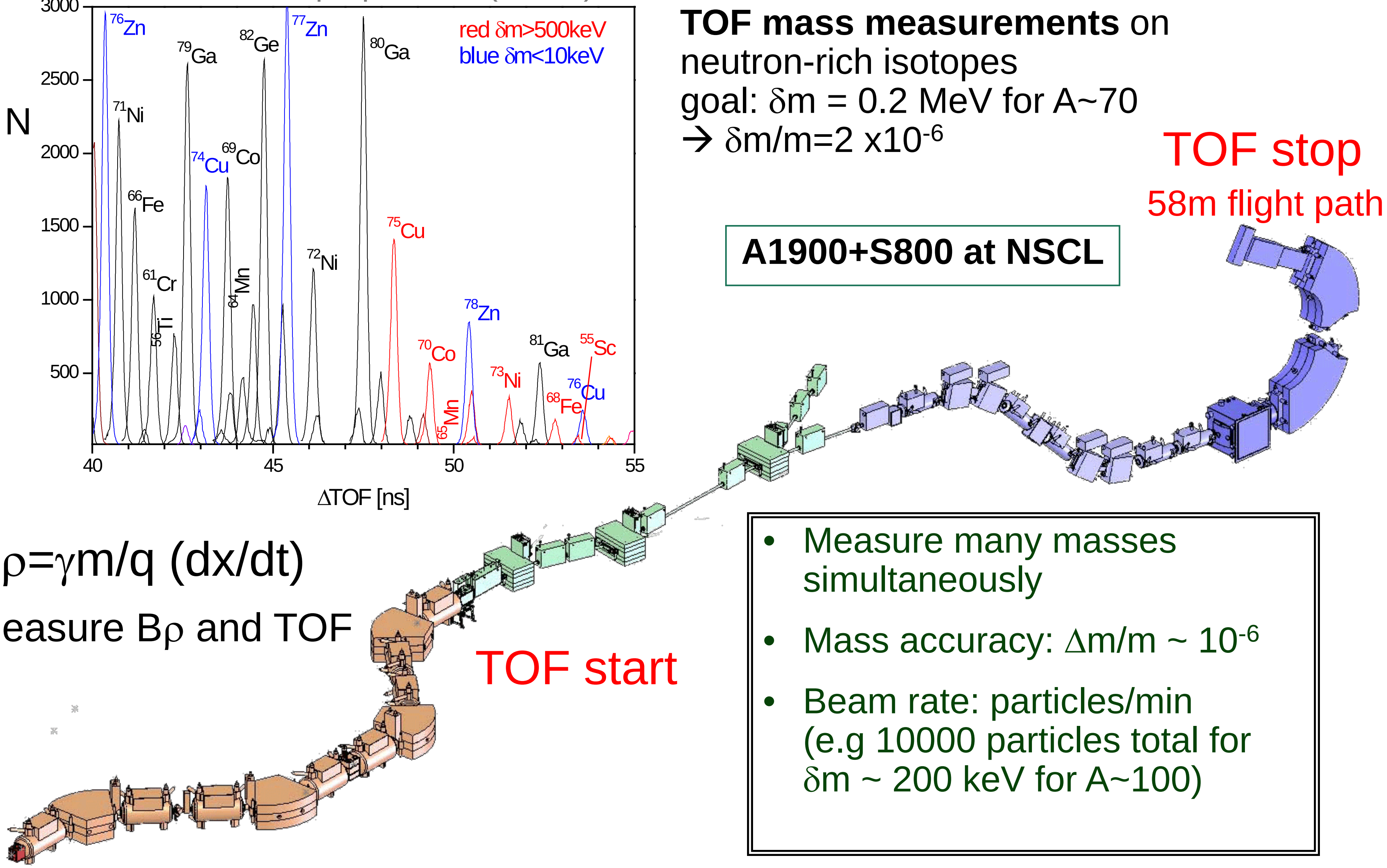
Dispersion

D = Δx m /Δm

Adapted from D. Lunney

TOF mass measurements
– *Spectrographs at NSCL*

A. Estrade, in preparation (NSCL)



TOF mass measurements on neutron-rich isotopes
goal: δm = 0.2 MeV for A~70
→ δm/m=2 x10^{-6}

TOF stop

58m flight path

A1900+S800 at NSCL

Bρ=γm/q (dx/dt)

Measure Bρ and TOF

TOF start

- Measure many masses simultaneously
- Mass accuracy: Δm/m ~ 10^{-6}
- Beam rate: particles/min (e.g 10000 particles total for δm ~ 200 keV for A~100)

Mass measurements in the ESR storage ring at GSI

F. Bosch, Lect. Notes Phys. 651, 137 (2004)

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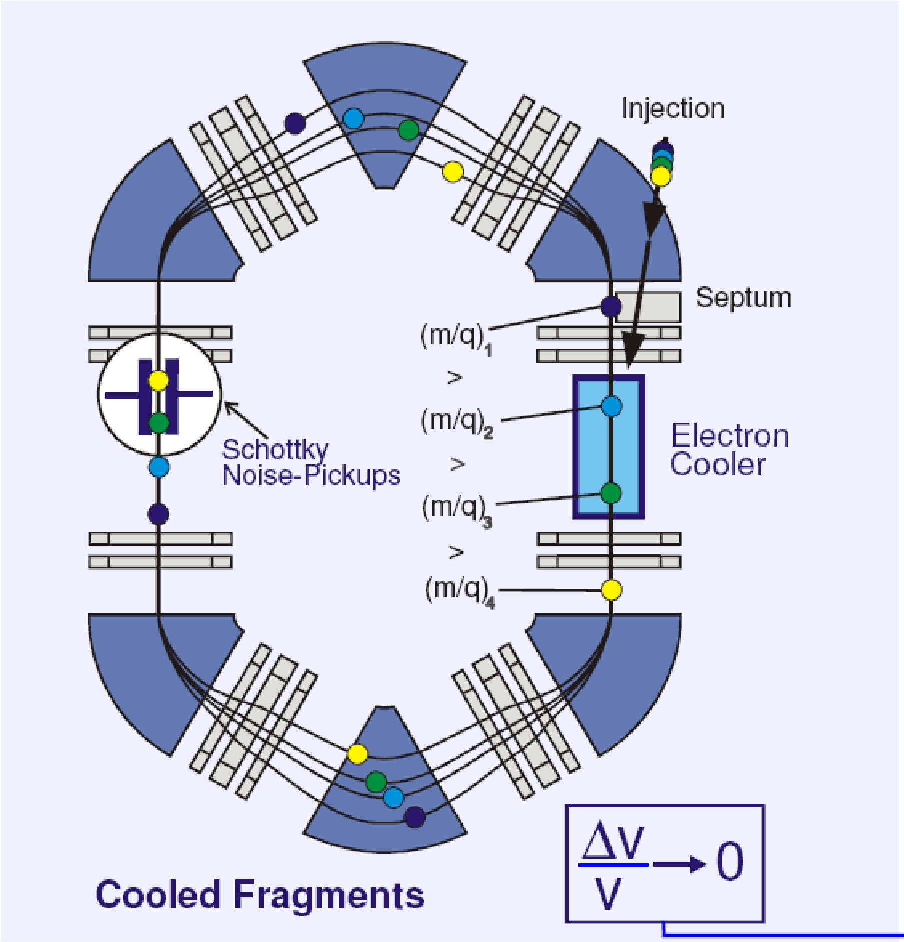
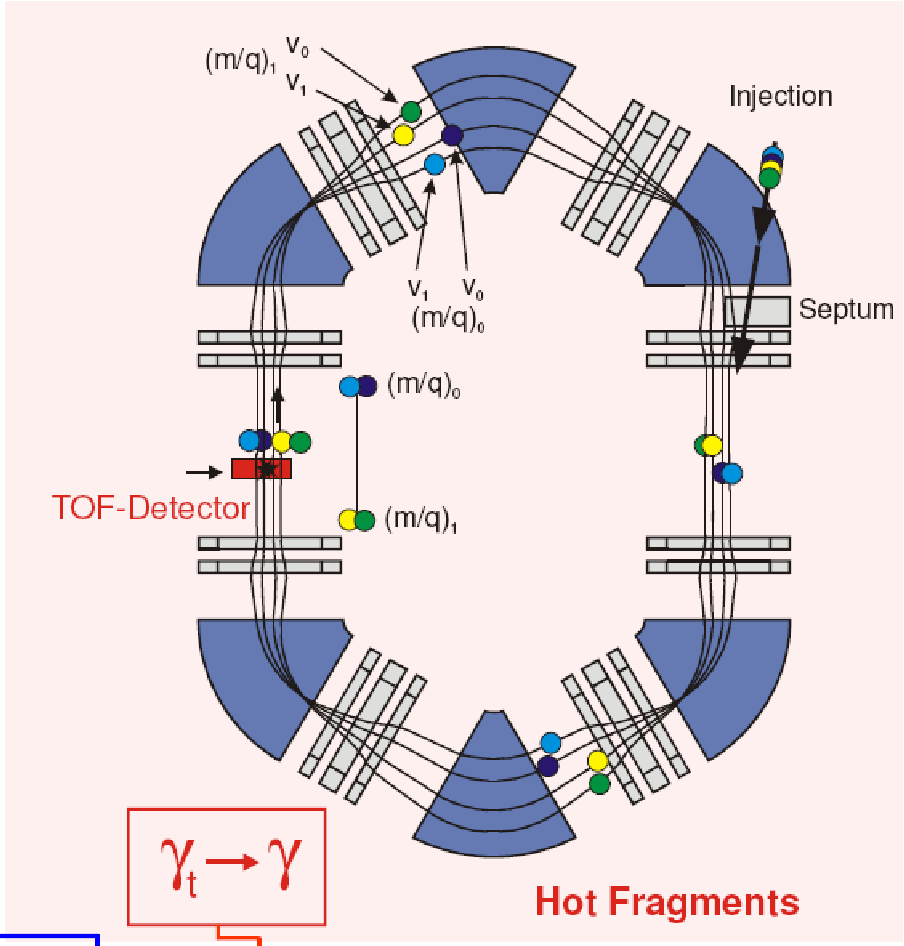
SCHOTTKY MASS SPECTROMETRY



$T_{1/2}>1$ s

ISOCHRONOUS MASS SPECTROMETRY



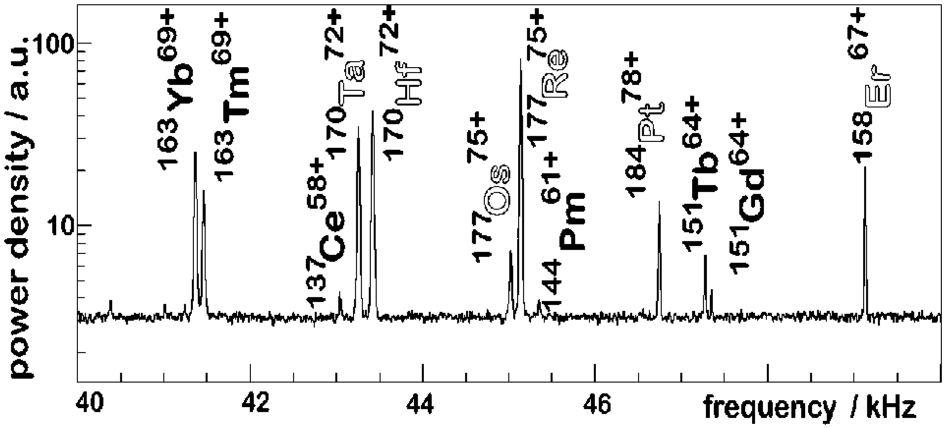
$T_{1/2}>10\ \mu$s

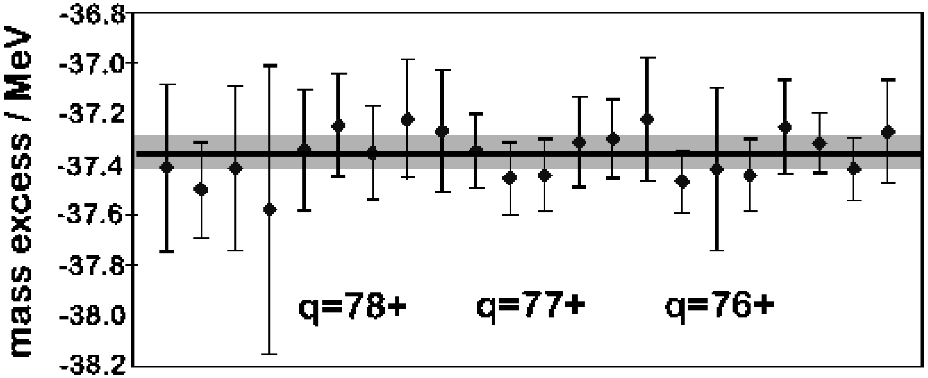
$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

γ_t: relative change in path length by turn relative to change in Bρ

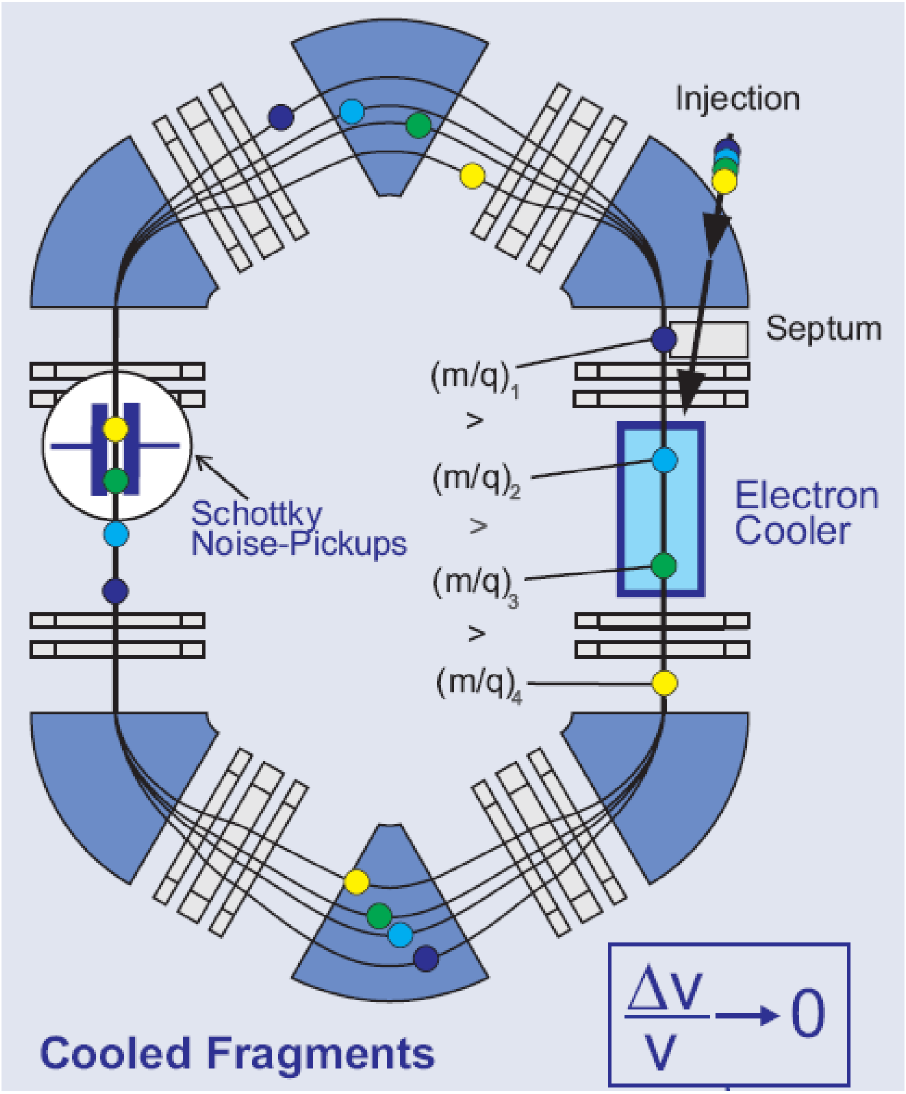
Mass measurements in the storage ring at GSI
I. Schottky mass spectrometry

- Schottky spectrometry in storage ring (GSI), e.g. ^{184}Pt





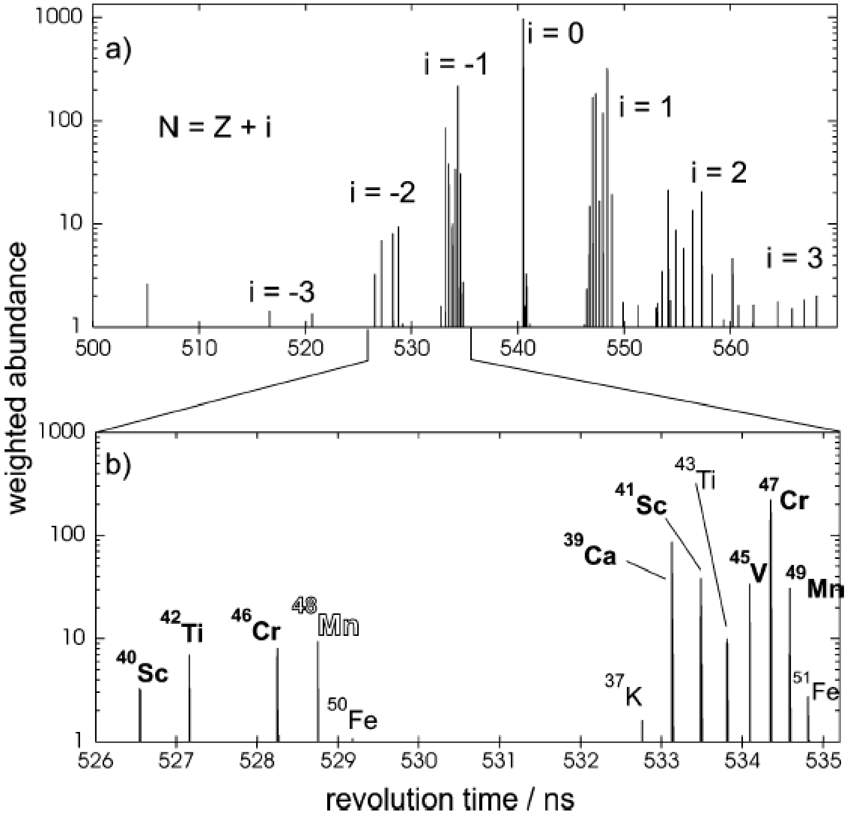
Mass excess for ^{184}Pt as determined in several runs using different reference isotopes and in different ionic charge states *q*. *(dm/m=5 10^{-7})*

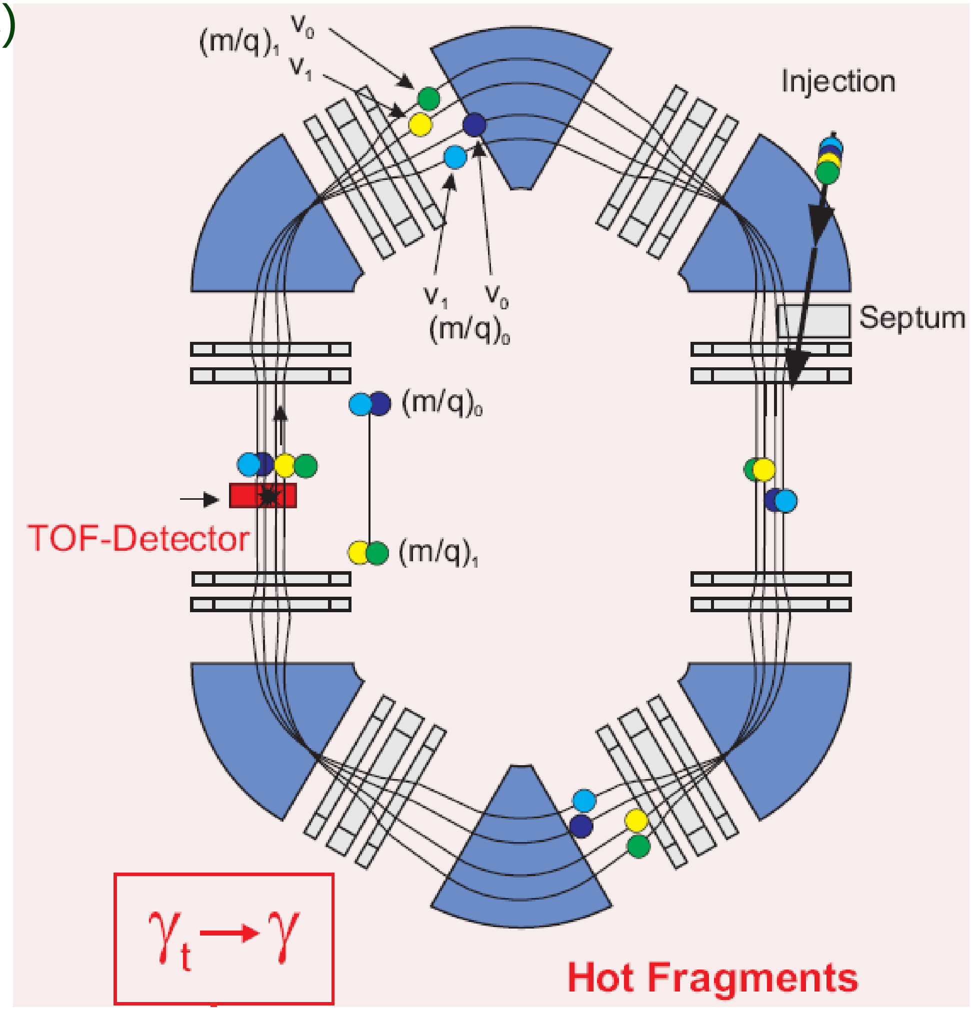


T. Radon et al., PRL 78, 4701 (1997)

Mass measurements in the storage ring at GSI
II. Isochronous mass spectrometry

- Mass measurement of short-lived ^{44}V, ^{48}Mn, ^{41}Ti and ^{45}Cr (X-ray burst models)

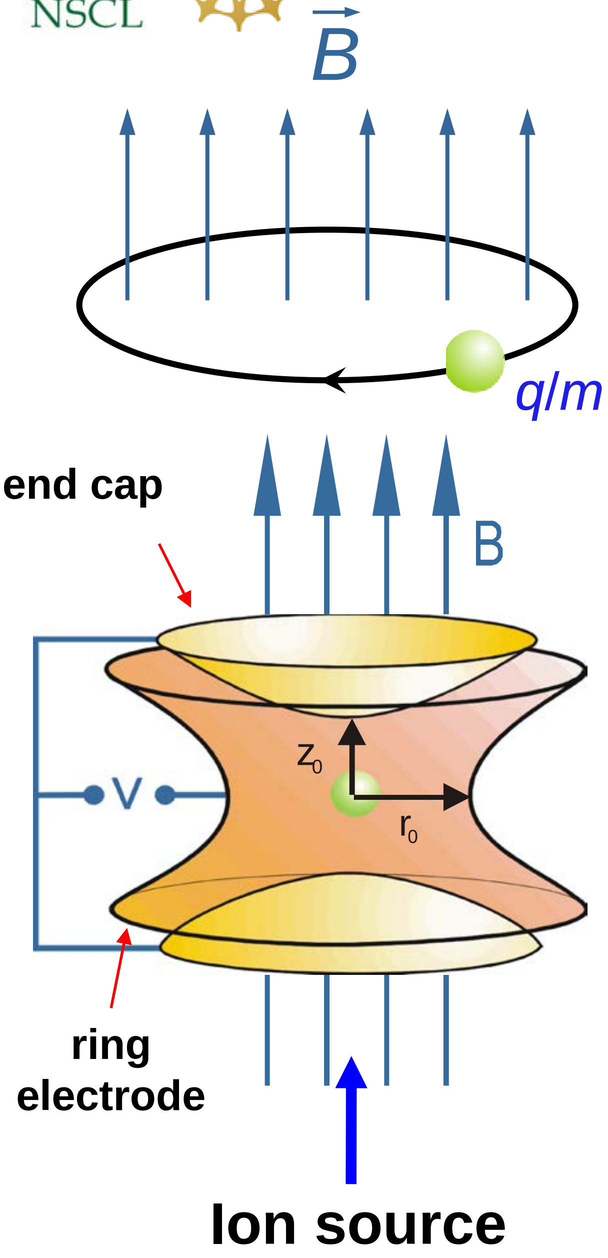




Accuracy of δm= 100-500 keV was achieved (lifetimes ~ 100 ms)

J. Stadlmann et al., PLB 586, 27 (2004)

Mass measurements with Penning traps



Mass measurement via determination of cyclotron frequency

$$f_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B$$

from characteristic motion of stored ions

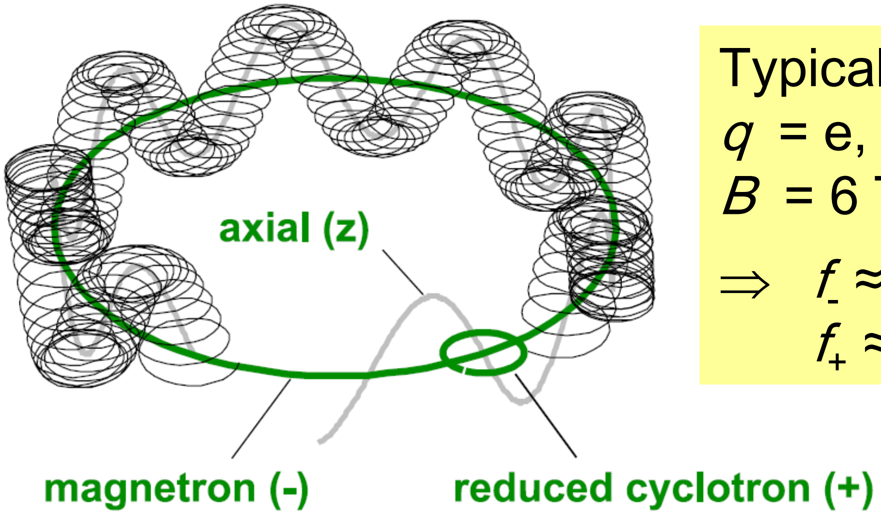
PENNING trap

- Strong homogeneous magnetic field of known strength B provides radial confinement
- Weak electric 3D quadrupole field provides axial confinement

Mass measurements with Penning traps

Motion of an ion is the superposition of three characteristic harmonic motions:

- axial motion (frequency f_z)
- magnetron motion (frequency f_-)
- modified cyclotron motion (frequency f_+)



Typical frequencies
q = e, m = 100 u,
B = 6 T

$\Rightarrow$ $f_- \approx 1$ kHz
$f_+ \approx 1$ MHz

Excite the cyclotron motion with multipolar RF (Goal: excite the cyclotron motion to resonance)

Transform radial to axial energy (gradient dB/dz) and eject ions

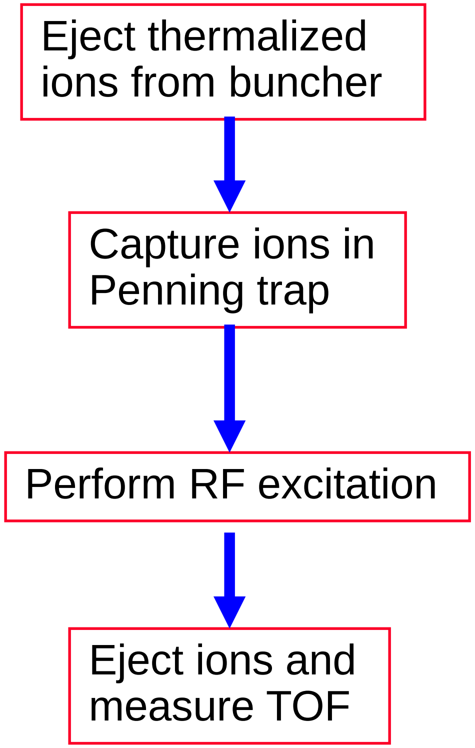
Measure time of flight (TOF) - the shorter TOF, the closer is the excitation frequency to the resonance

The frequencies of the radial motions obey the relation

$$f_+ + f_- = f_c = \frac{1}{2\pi}\cdot\frac{q}{\boxed{m}}\cdot B$$

Adapted from K. Blaum

Mass measurements with Penning traps

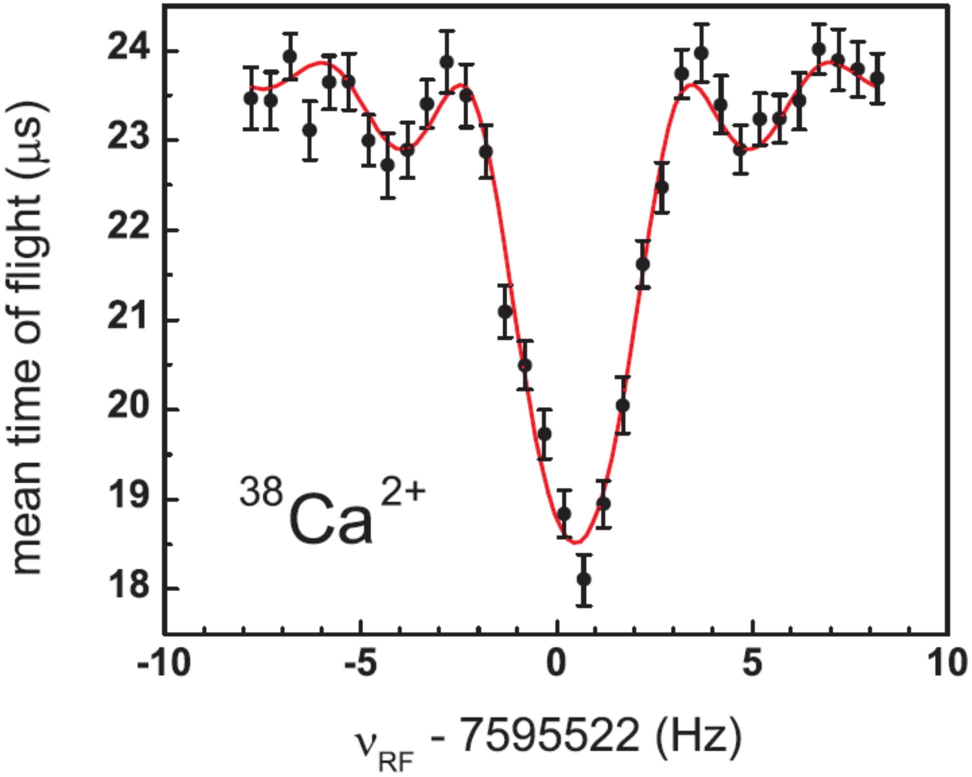


Eject thermalized ions from buncher

Capture ions in Penning trap

Perform RF excitation

Eject ions and measure TOF



ME=-22058.53(28) keV

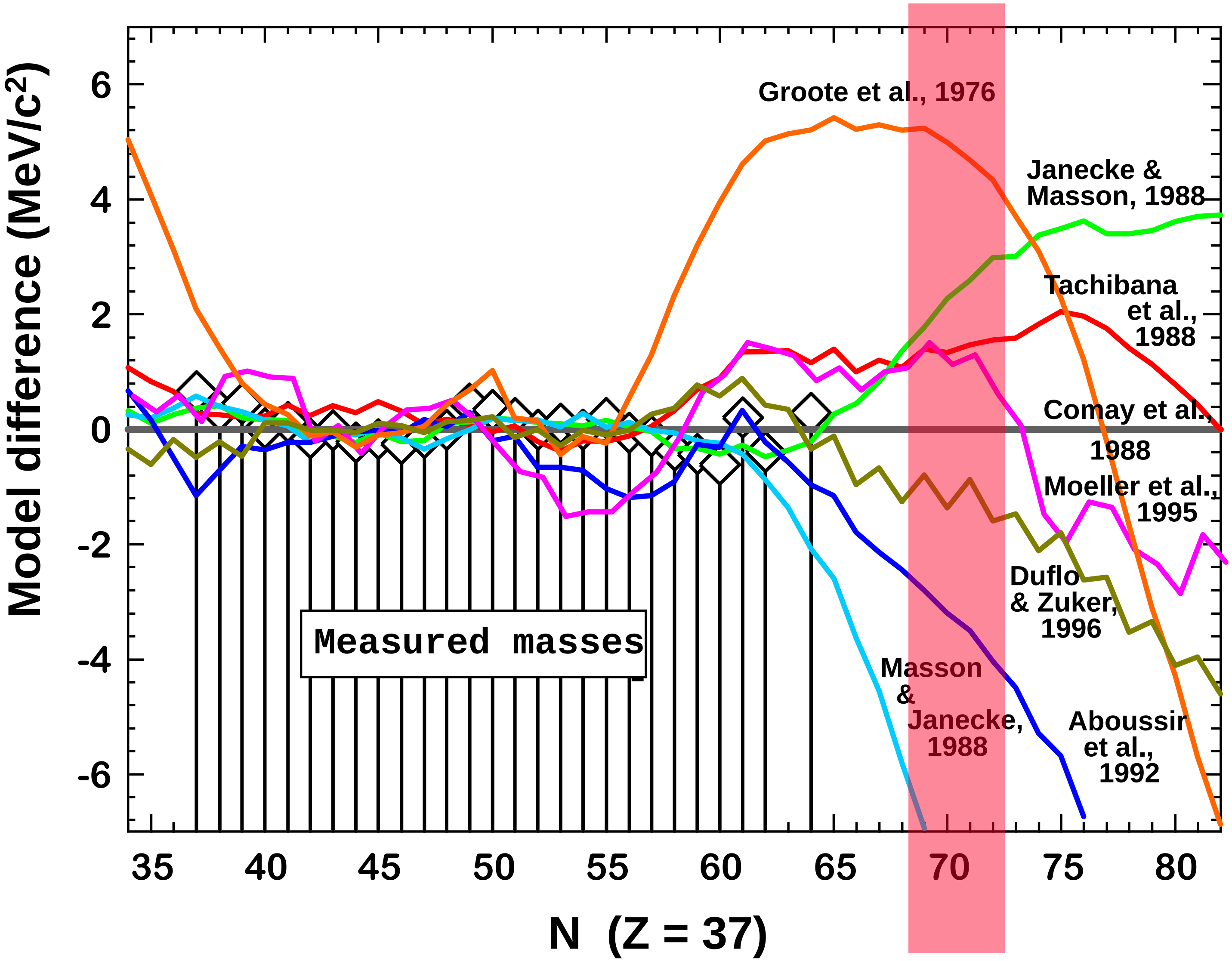
δm=280 eV

G. Bollen et al., PRL 96, 152501 (2006)

Masses – what are they good for?

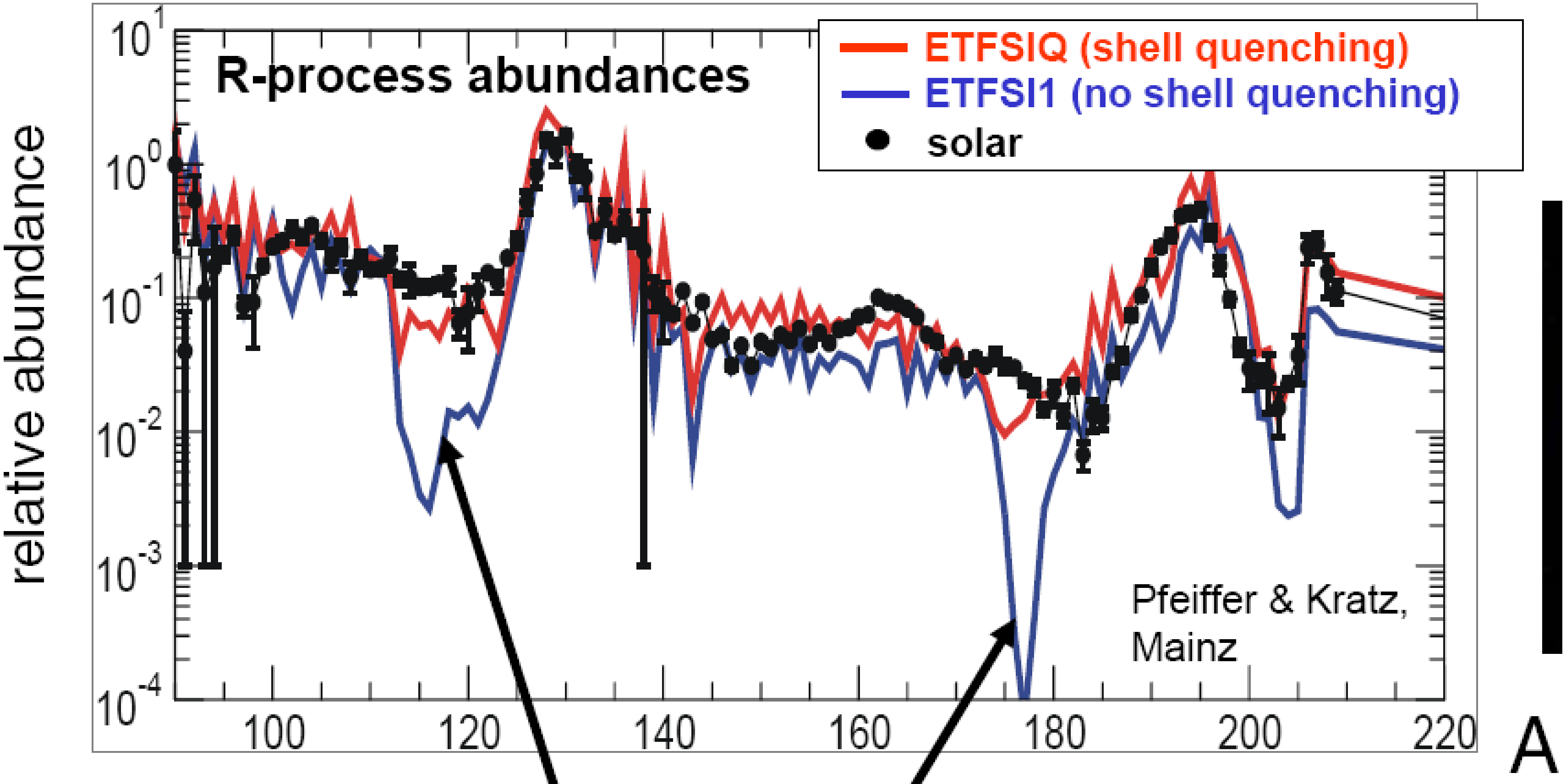
- Structure information
  - Shell closures and deformation from separation energies ($\delta m/m < 10^{-5}$)
- Astrophysics (Nucleosynthesis)
  - r process ($\delta m/m < 10^{-5}$, $\delta m < 10$ keV)
  - rp process ($\delta m/m \sim 10^{-7}$)
- Fundamental interactions and symmetries ($\delta m/m<10^{-8}$)
  - CVC
  - CKM

Masses – what are they good for?
Constrain theory



Needed for r-process

Masses – what are they good for?
Nuclear astrophysics



Difference due to shell quenching for neutron-rich nuclei, or a problem with astrophysical model?

Masses – what are they good for?
Fundamental interactions/symmetries

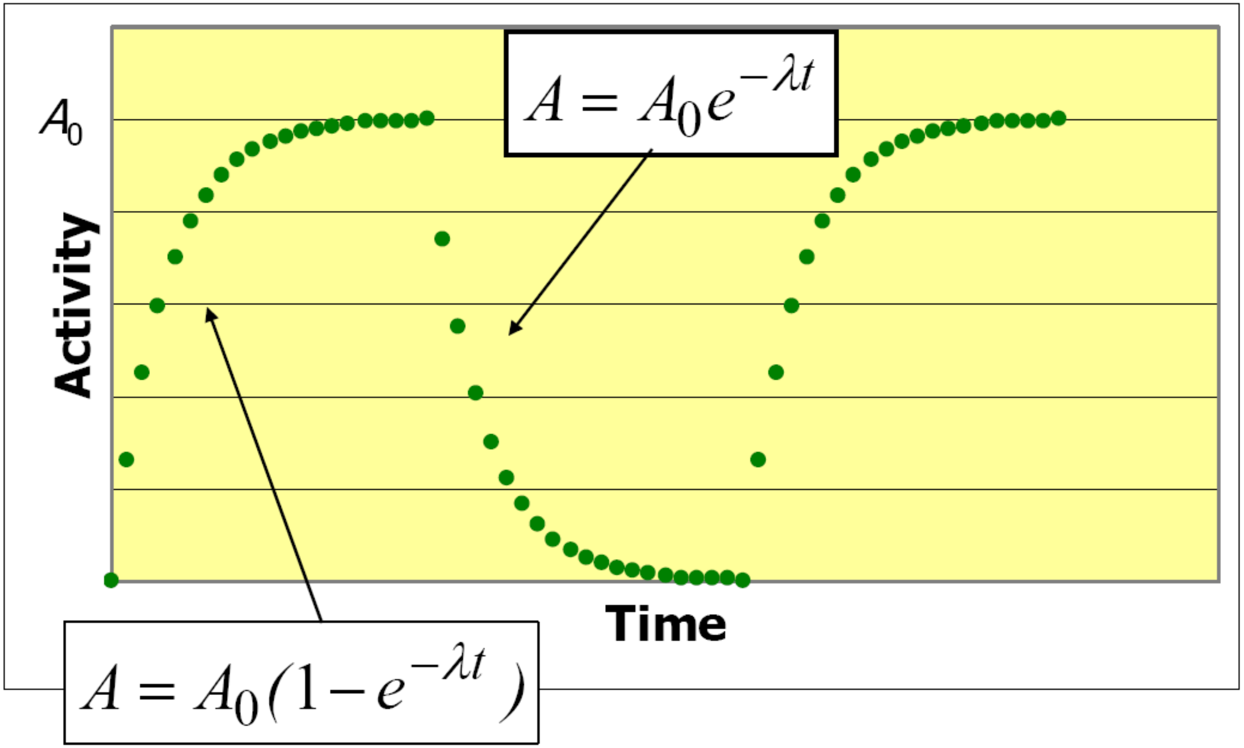
Physics beyond the Standard Model

(required precision: as good as possible, at least: $\delta m/m<10^{-8}$)

- Conserved vector current (CVC) hypothesis
- Unitarity of the Cabbibo-Kobayashi-Maskawa (CKM) matrix

Half-lives

Bulk activity measurements



$A = A_0 e^{-\lambda t}$

$A = A_0(1 - e^{-\lambda t})$

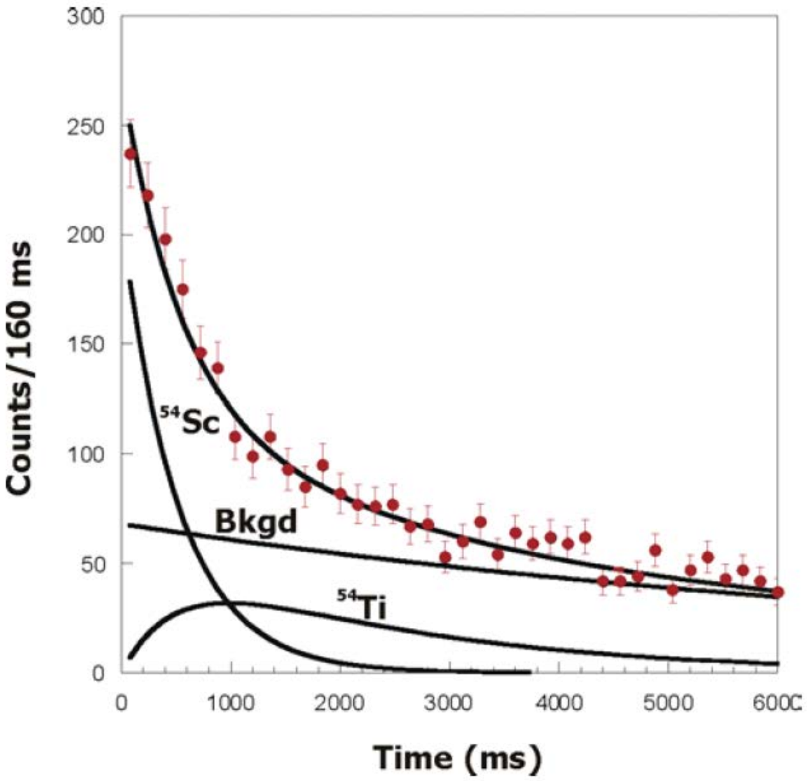
$\lambda = \ln 2/t_{1/2}$

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

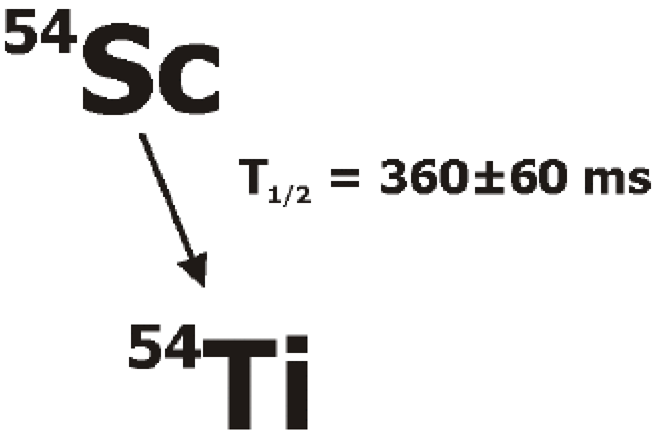
Implant activity in active stopper material for time t_i. Cease implantation and observe decay for time t_d.

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

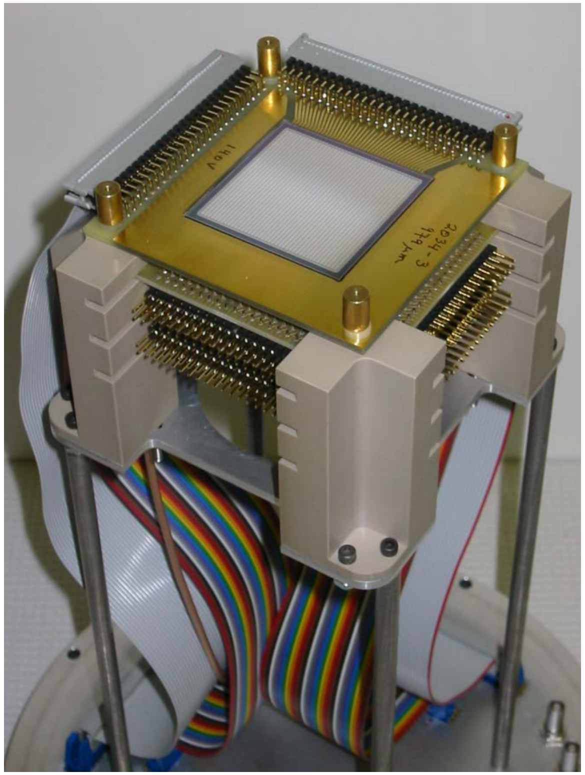
^{54}Ti

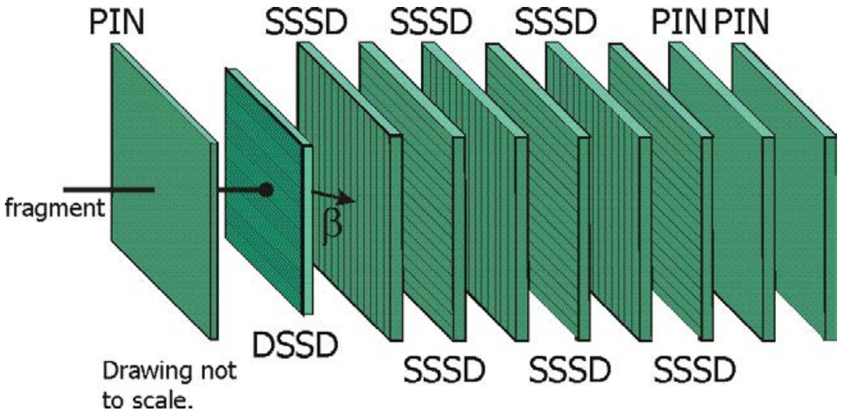
- **Reduced background from in-flight tracking and identification of individual isotopes in the beam on a particle-by-particle basis**

Adapted from P. F. Mantica

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

Beta counting systems
Example: BCS at NSCL



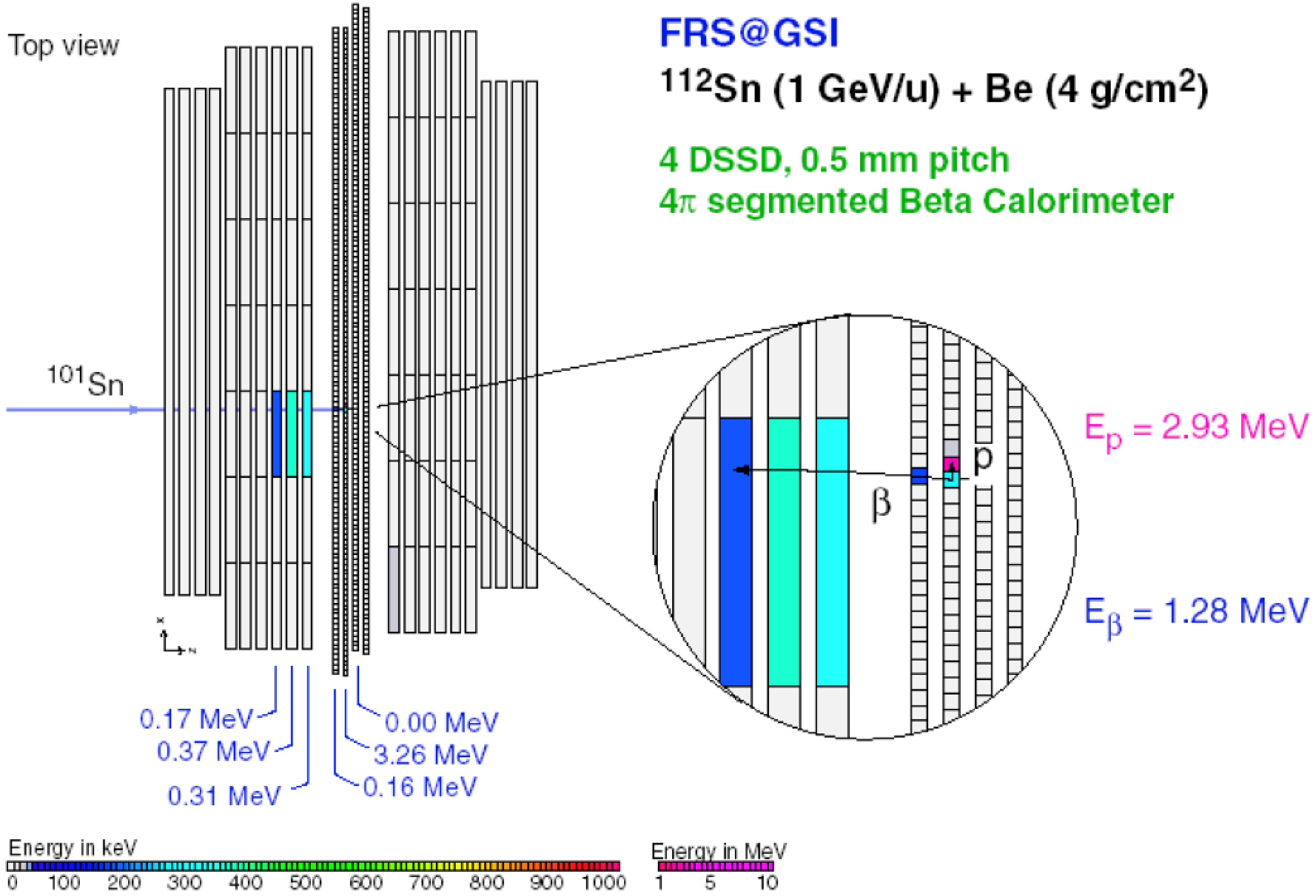


Permits the correlation of fragment implants and subsequent beta decays on an event-by-event basis

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



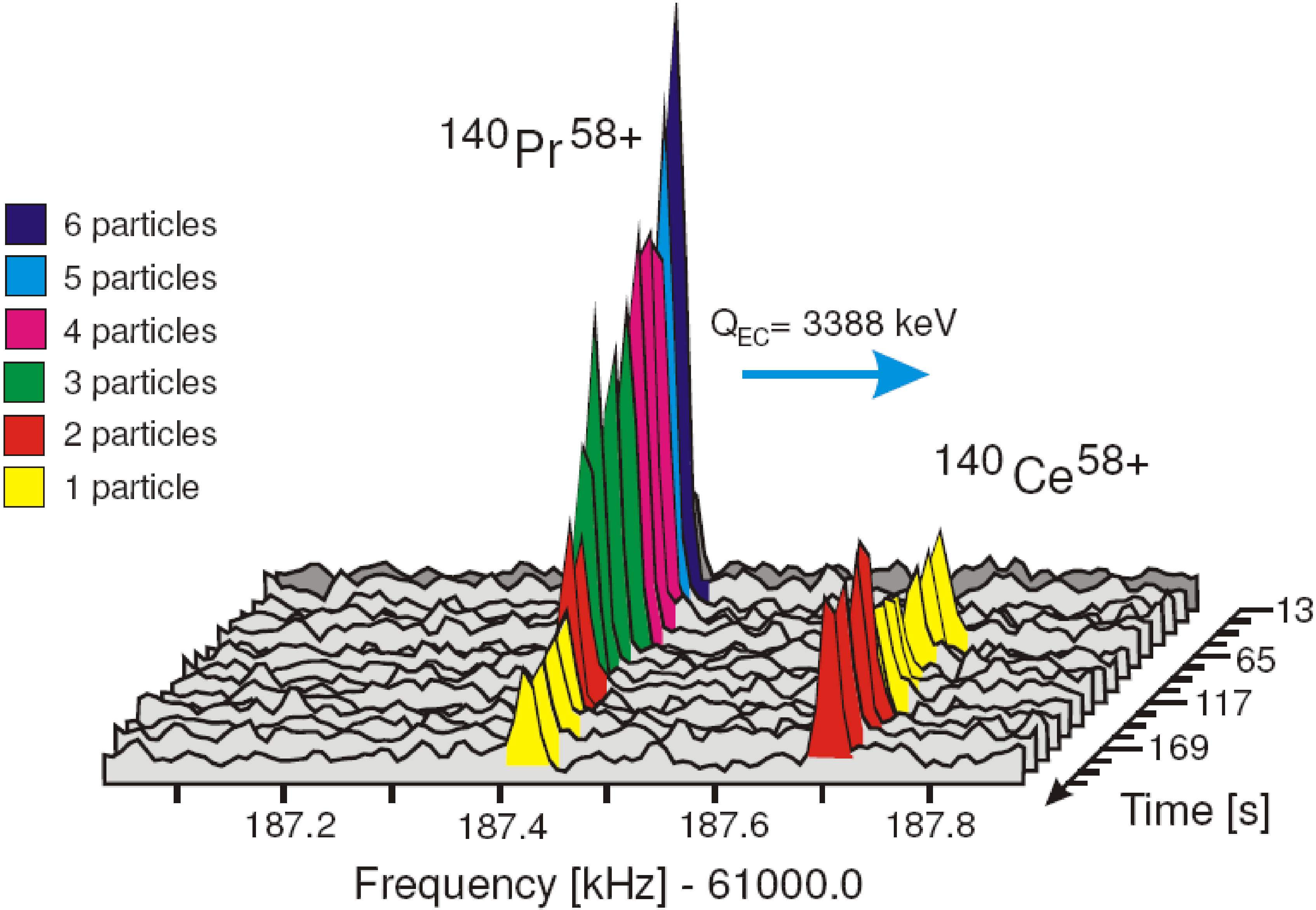
FRS@GSI

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

4 DSSD, 0.5 mm pitch
4π segmented Beta Calorimeter

A. Stolz (2003)

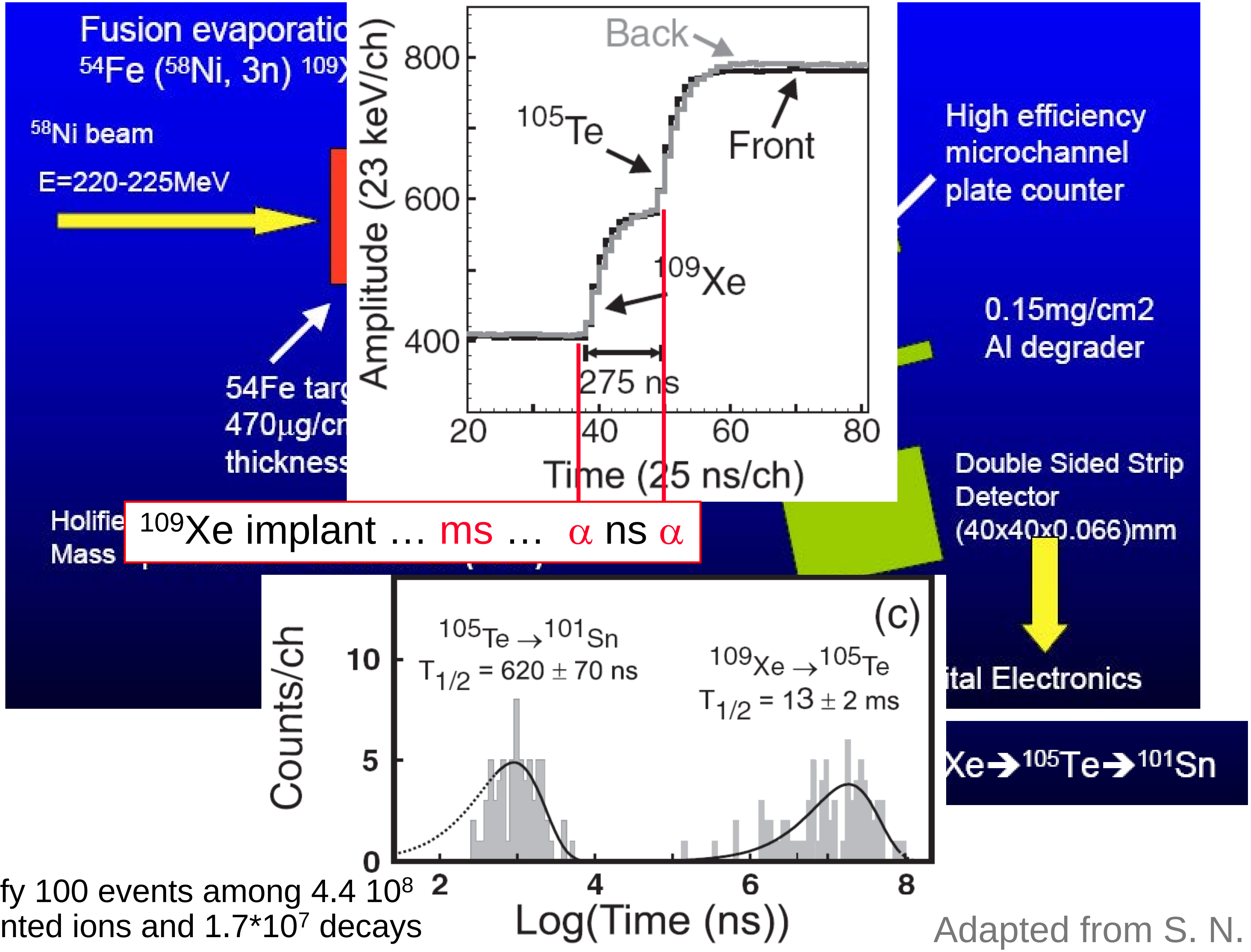
Caught in the act:
^{140}Pr → ^{140}Ce β-decay in the ESR@GSI



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)



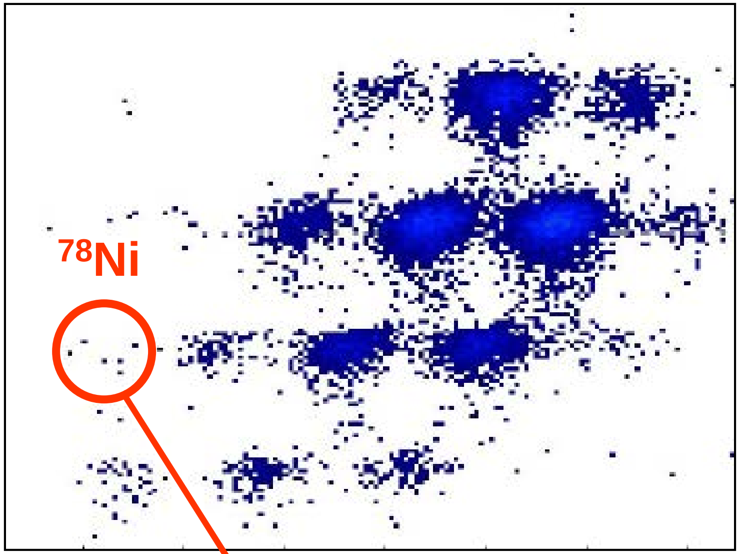
^{109}Xe implant … ms … α ns α

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

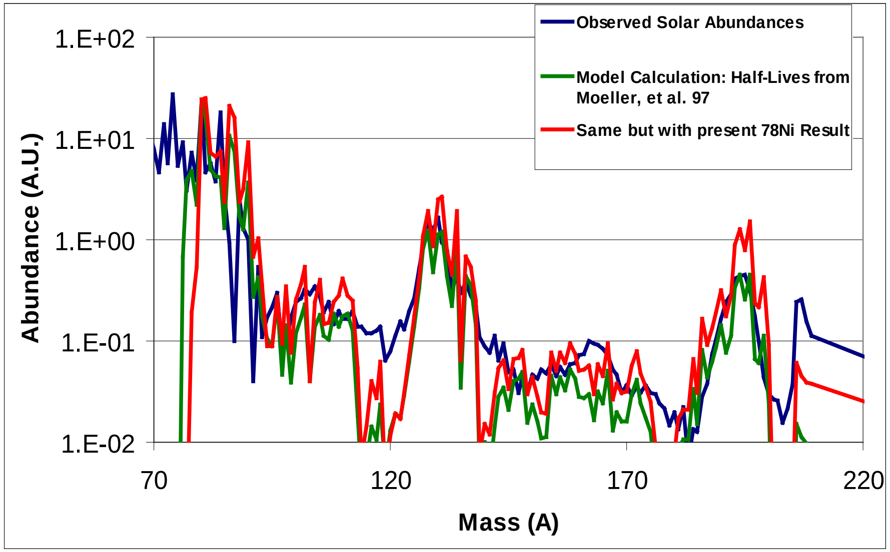


Measured half-life of ^{78}Ni with 11 events This is the most neutron rich of the 10 possible classical doubly-magic nuclei in nature.

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

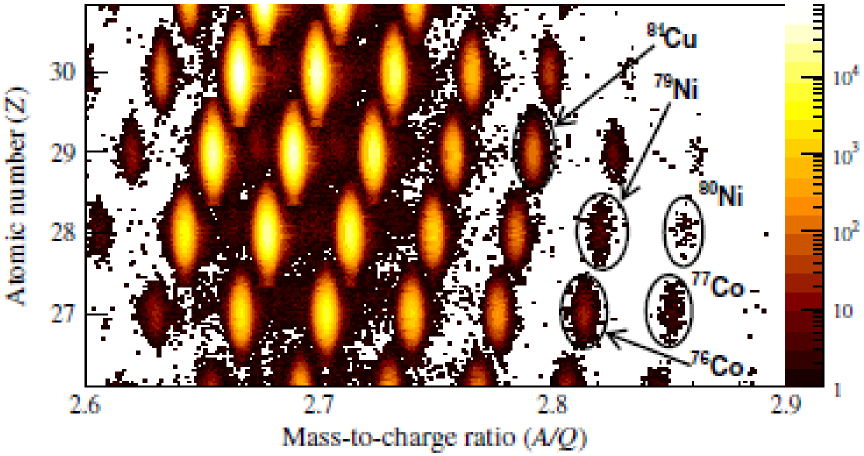
→ the synthesis of heavy elements in nature proceeds faster than previously assumed

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

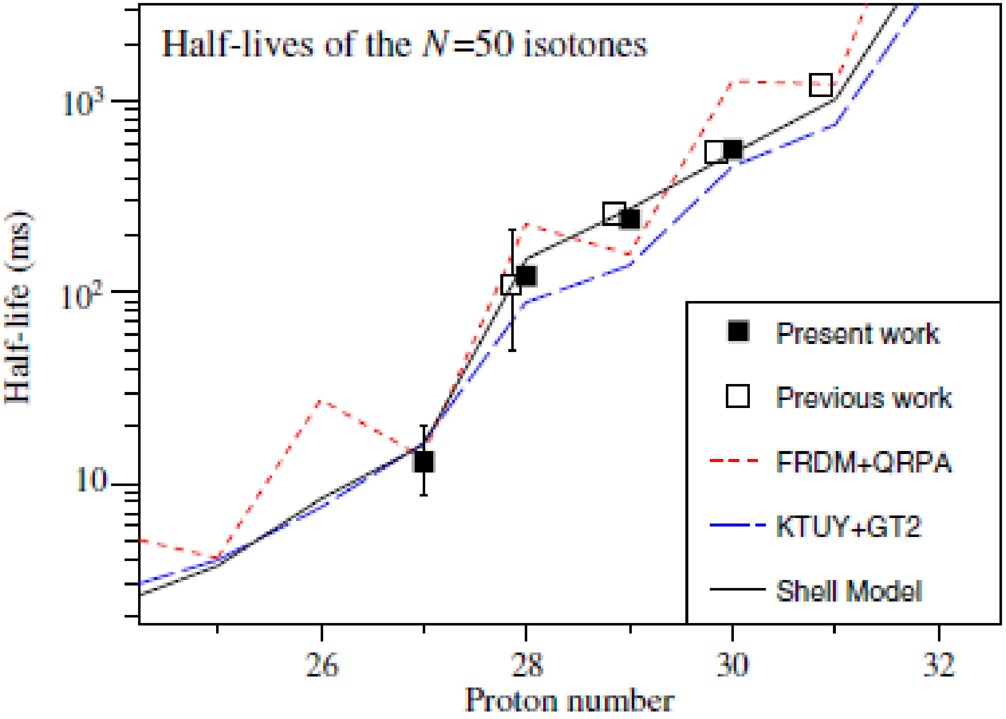
Adapted from H. Schatz

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

Particle identification in rare-isotope beam from RIBF at RIKEN



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



Very similar experimental scheme

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

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
  - Nuclear masses – 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

End