Ion trap based mass measurements of short-lived nuclei at ISOLTRAP and SHIPTRAP

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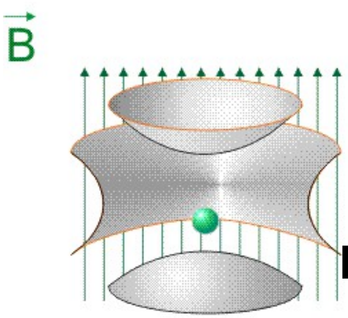
https://physik.uni-greifswald.de/ag-schweikhard/

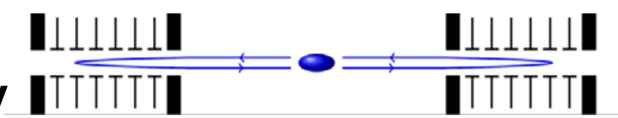
for the
ISOLTRAP and SHIPTRAP collaborations



Penning-trap and

Time-of-Flight

Mass Spectrometry



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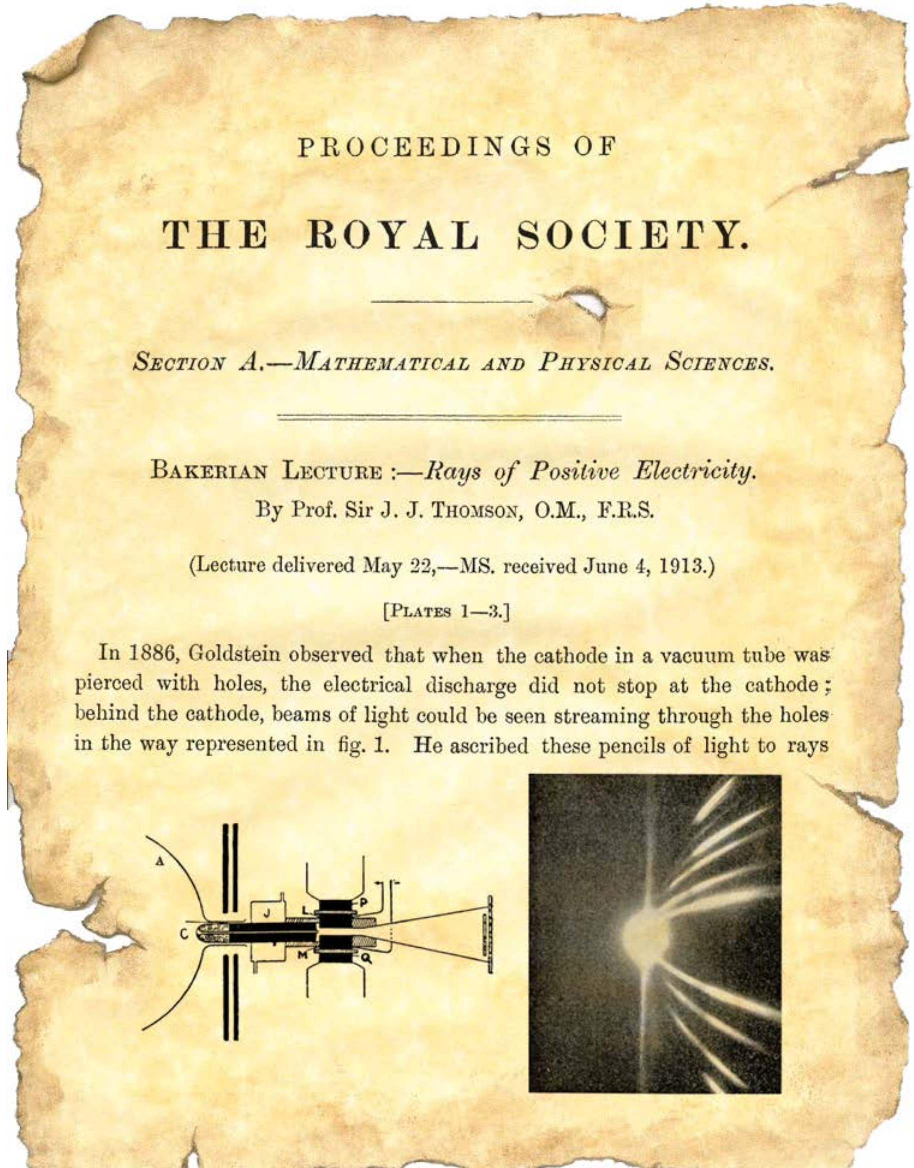
Federal Ministry of Education and Research

at ISOLTRAP (cern.ch) = https://isoltrap.web.cern.ch/
and GSI - SHIPTRAP
= https://www.gsi.de/work/forschung/appamml/atomphysik/anlagen_und_experimente/shiptrap

1913, J.J. Thomson
"Rays of Positive Electricity"
Observation of line at mass 22
in addition to ^{20}Ne

The work was further pursued by
Francis W. Aston
Nobel Prize
in Chemistry, 1922,

"for his discovery, by means of his mass spectrograph, of isotopes, in a large number of non-radioactive elements, and for his enunciation of the whole-number rule".



PROCEEDINGS OF

THE ROYAL SOCIETY.

SECTION A.—MATHEMATICAL AND PHYSICAL SCIENCES.

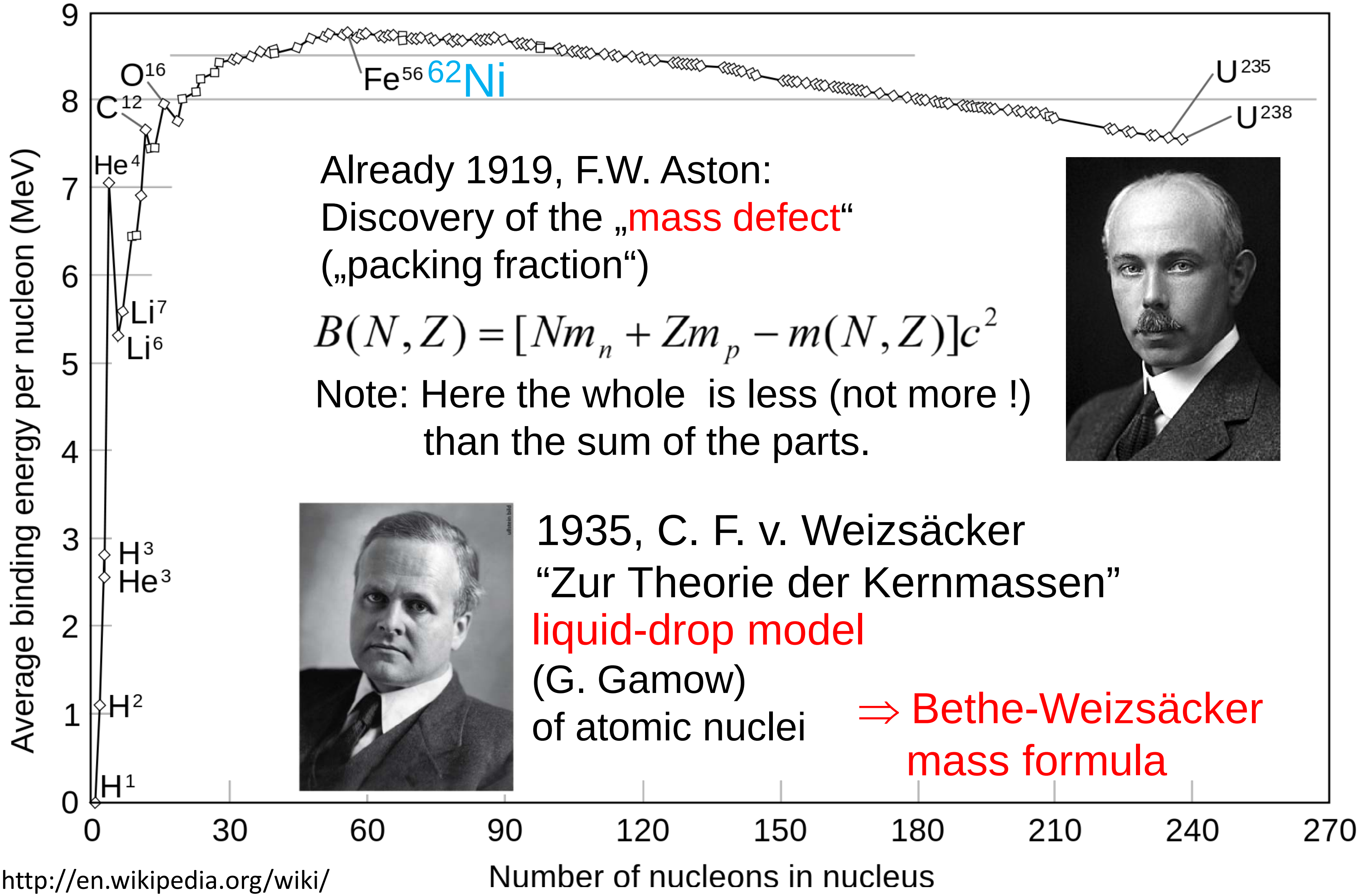
BAKERIAN LECTURE :—*Rays of Positive Electricity.*
By Prof. Sir J. J. THOMSON, O.M., F.R.S.

(Lecture delivered May 22,—MS. received June 4, 1913.)

[PLATES 1—3.]

In 1886, Goldstein observed that when the cathode in a vacuum tube was pierced with holes, the electrical discharge did not stop at the cathode; behind the cathode, beams of light could be seen streaming through the holes in the way represented in fig. 1. He ascribed these pencils of light to rays

Background: MS for Nuclear Physics, History



Already 1919, F.W. Aston:
Discovery of the „mass defect“
(„packing fraction“)

$$B(N,Z) = [Nm_n + Zm_p - m(N,Z)]c^2$$

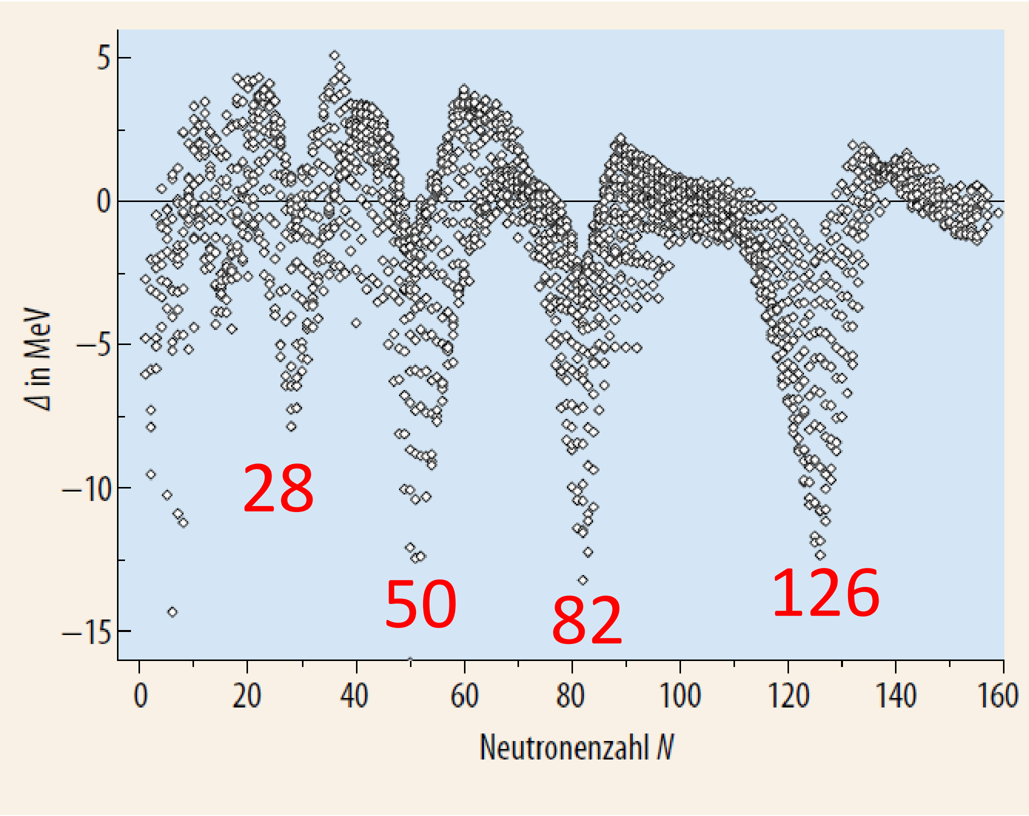
Note: Here the whole is less (not more !)
than the sum of the parts.

1935, C. F. v. Weizsäcker
“Zur Theorie der Kernmassen”
liquid-drop model
(G. Gamow)
of atomic nuclei

⇒ Bethe-Weizsäcker
mass formula

http://en.wikipedia.org/wiki/
Nuclear_binding_energy

Deviations from the Bethe-Weizsäcker mass formula

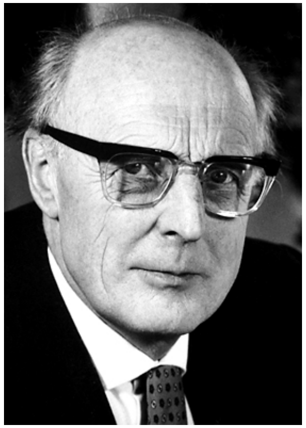


"magic numbers"

⇒ nuclear structure

Shell model

1949 Göppert-Mayer & Jensen



1963 

Separation Energies $E = \Delta m\, c^2$ <=> $\Delta m = E/c^2$

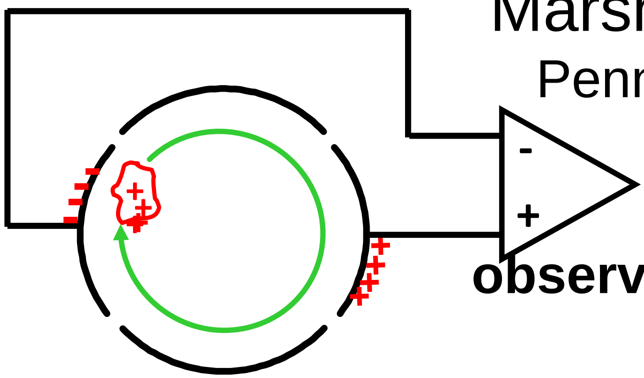
Problem: $\frac{\Delta m}{m} \ll 1$ with order of magn. $\frac{1\mathrm{keV}}{100\mathrm{GeV}} = 10^{-8}$

FT-ICR MS for Nuclear Physics ???

Fourier -Transform Ion-Cyclotron-Resonance Mass Spectrometry

Marshall, Comisarow, 1974: FT-ICR MS

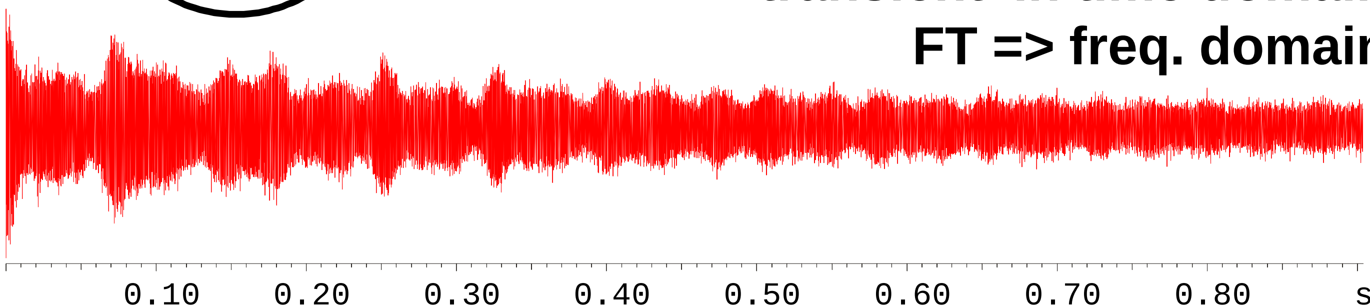
Penning trap for analytical mass spectrometry

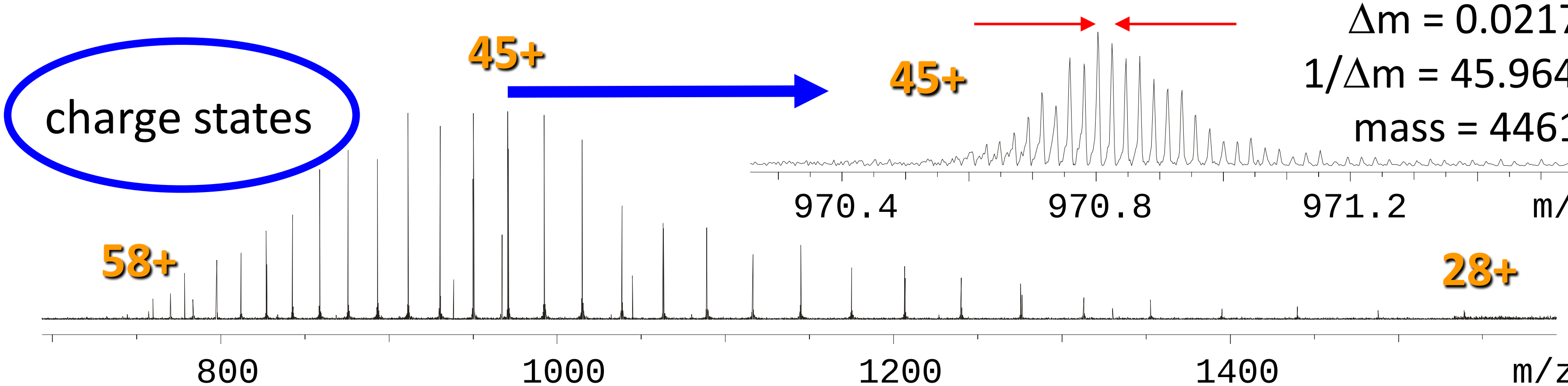


after broad-band excitation:
observe image charges in electroes
transient in time domain
FT => freq. domain

$$\omega_c = \frac{q}{m}B$$

$$\frac{m}{q} = \frac{B}{\omega_c}$$





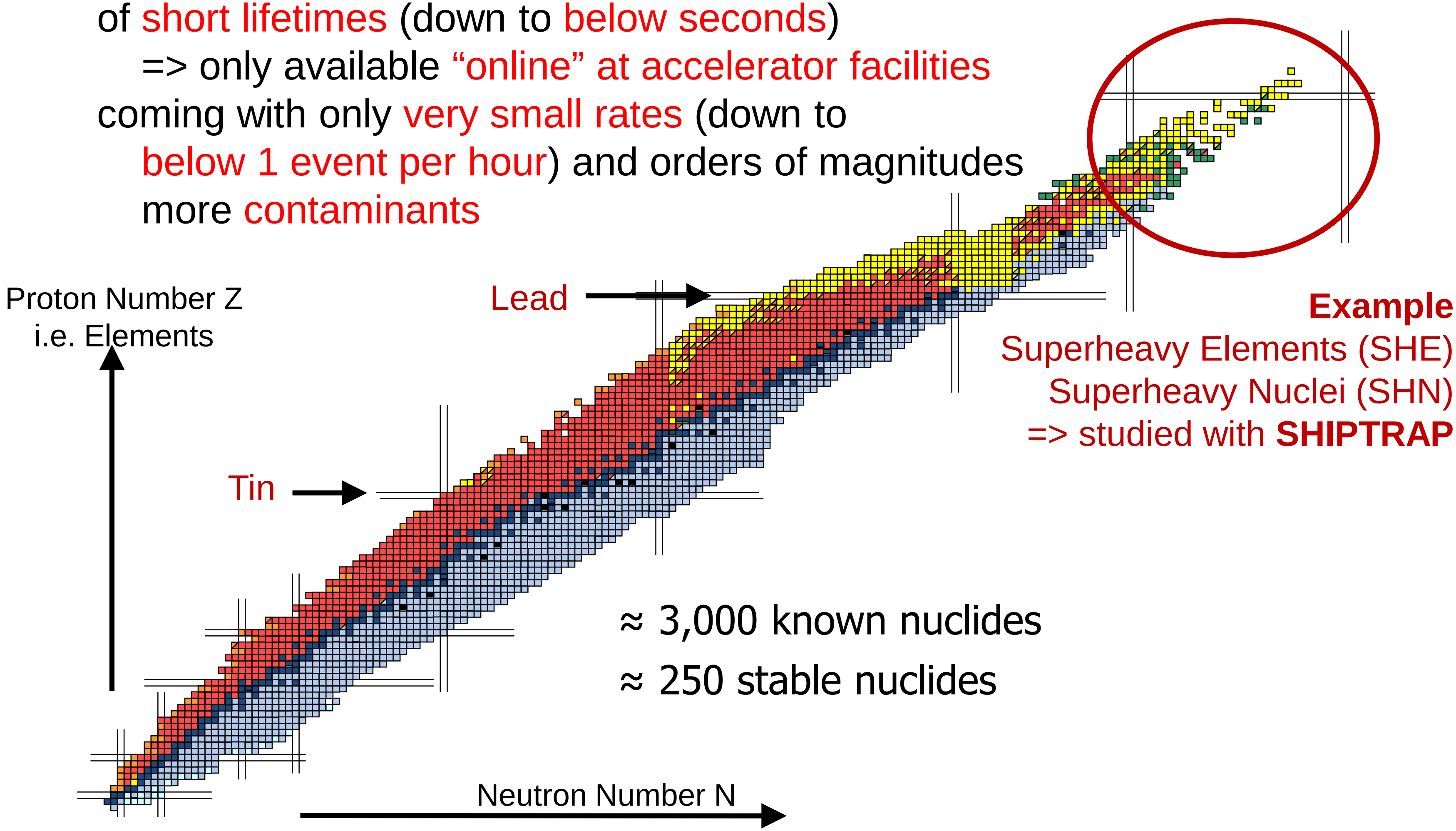
$\Delta m = 0.02176$ u

$1/\Delta m = 45.964$ / u

mass = 44610 u

Background: Segré chart of nuclei

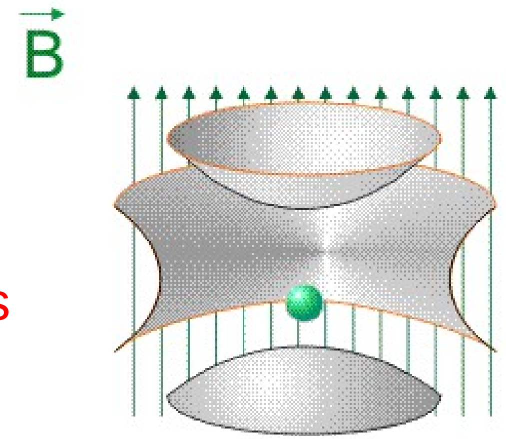
But: To study nuclear structure we are interested in nuclides as far away from stability as possible
= exotic nuclei = rare nuclei
of short lifetimes (down to below seconds)
=> only available "online" at accelerator facilities
coming with only very small rates (down to below 1 event per hour) and orders of magnitudes more contaminants



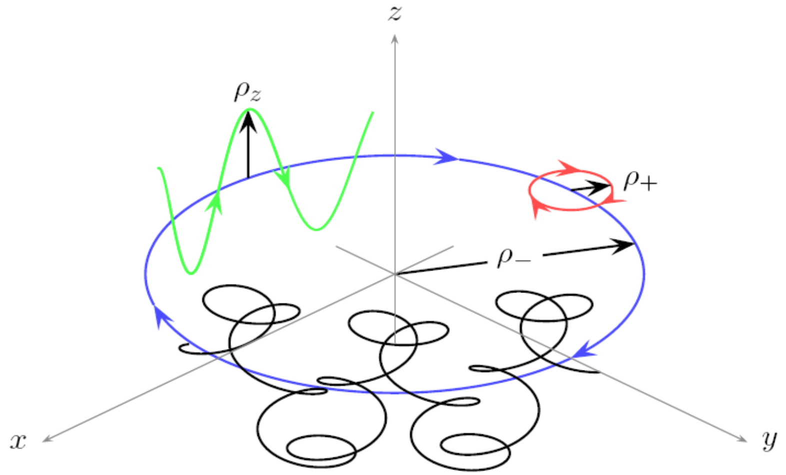
Penning trap Mass Measurements

Like FT- ICR MS
but without FT

Not broad-band
but with single (singly-charged) ions



cyclotron motion in magnetic field,
but plus axial confinement
=> motion more complicated



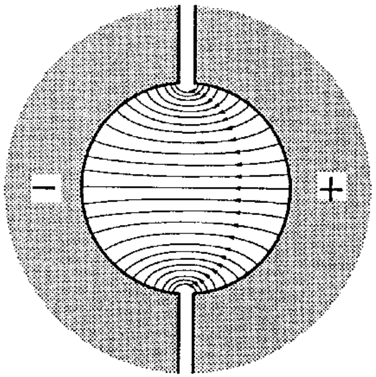
axial motion with trapping freq. ω_z
cycl. motion with reduced cycl. freq. ω_+
plus additional magnetron motion with
typically much lower freq. ω_-

But cycl. freq. ω_+
and magnetron freq. ω_-
add up to

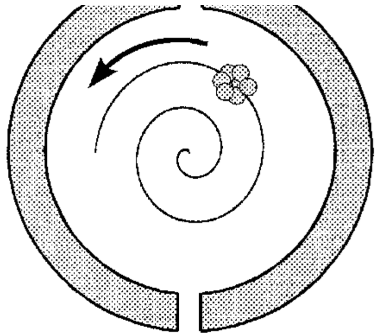
$$\omega_c = \frac{qB}{m} = \omega_+ + \omega_-$$

Penning trap, radial modes (cyclotron/magnetron motion)

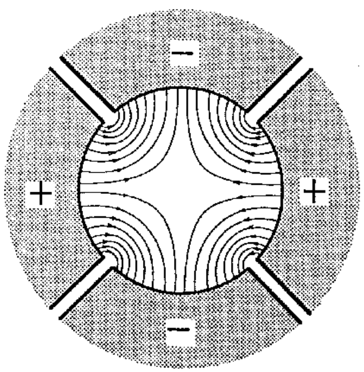
dipolar excitation



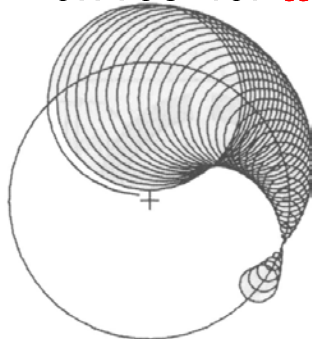
resonances at ω_+
and, used here, ω_-



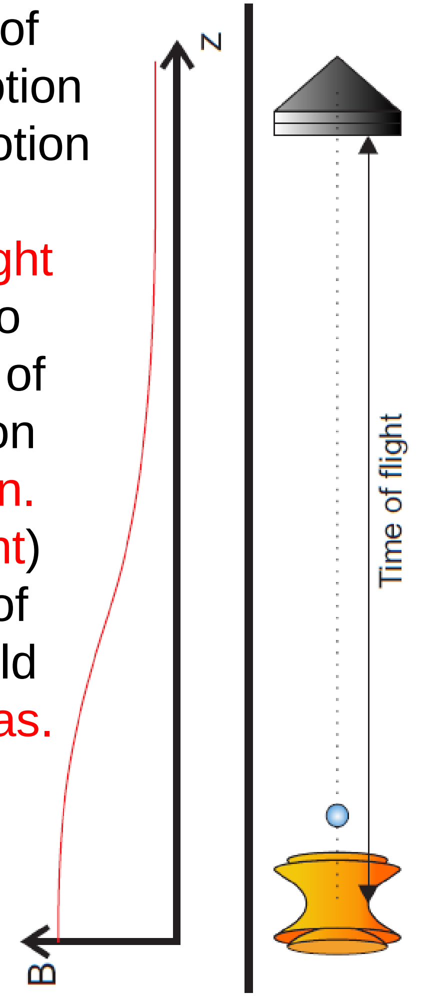
quadrupolar excitation



conversion to and fro
on res. for $\omega_c = \frac{qB}{m}$

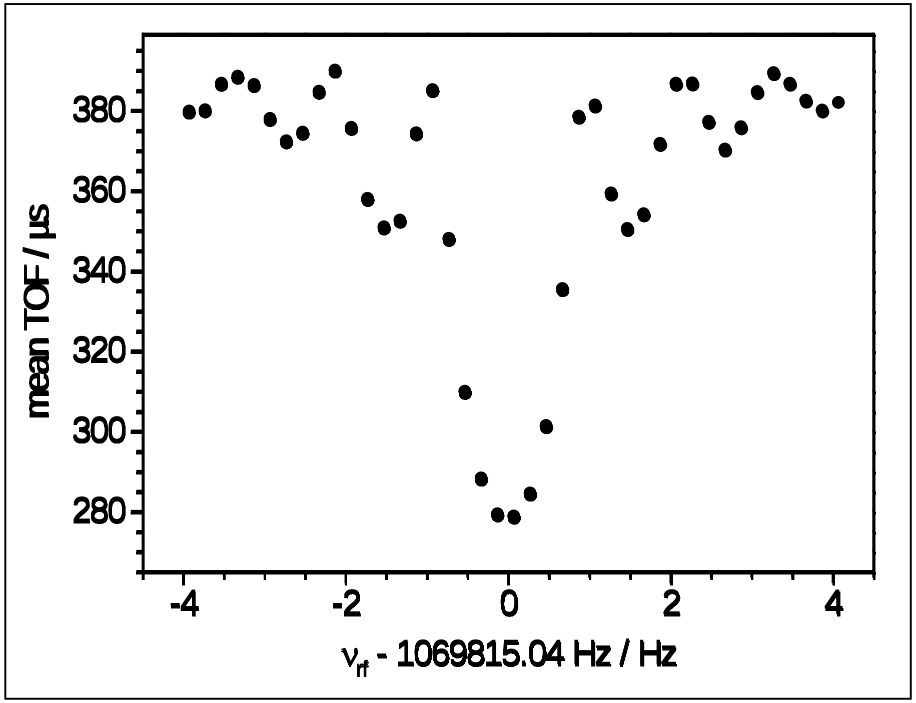


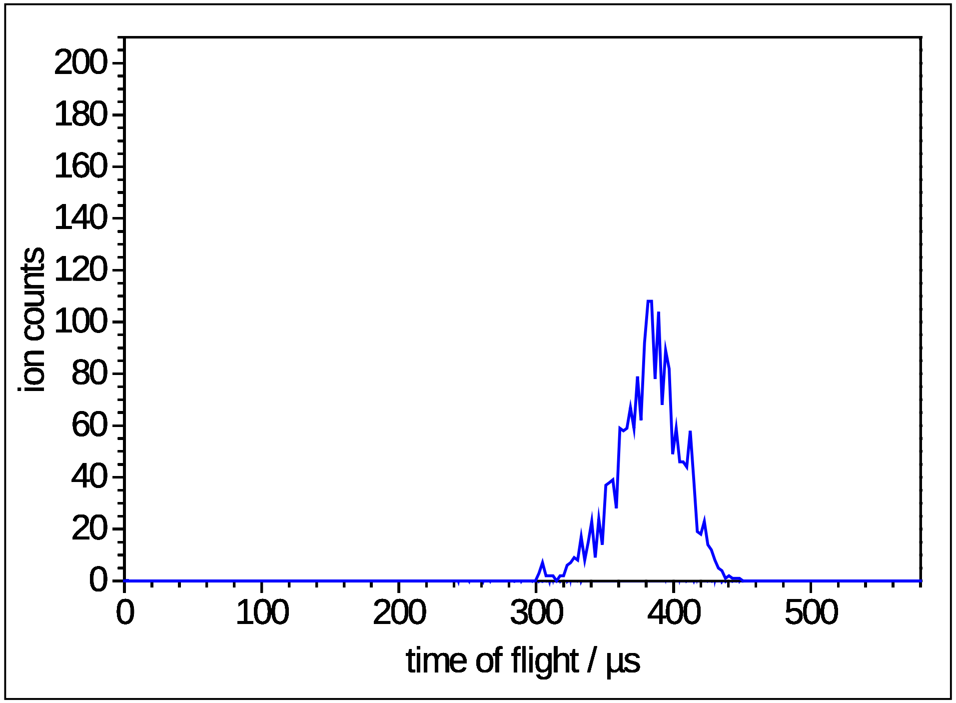
conversion of
magnetron motion
to cyclotron motion
detected
by time-of-flight
effect due to
acceleration of
circulating ion
(orbital magn.
dipol moment)
in gradient of
magnetic field
=> mass meas.



Time-of-Flight ICR MS for nuclear physics

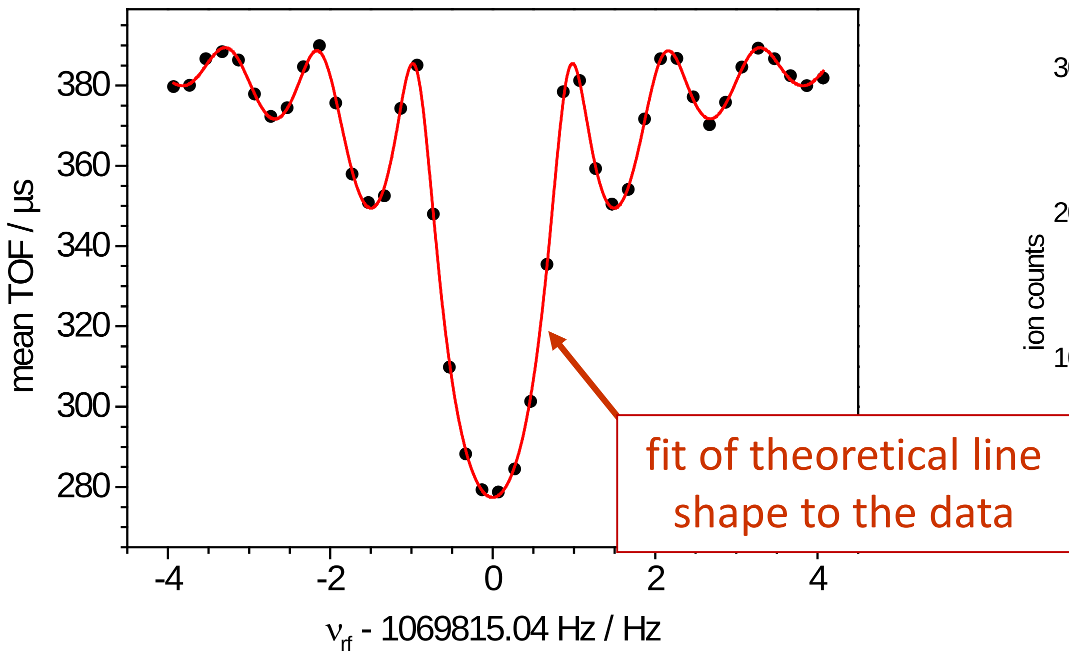
mean ToF ← Time-of-Flight spectrum

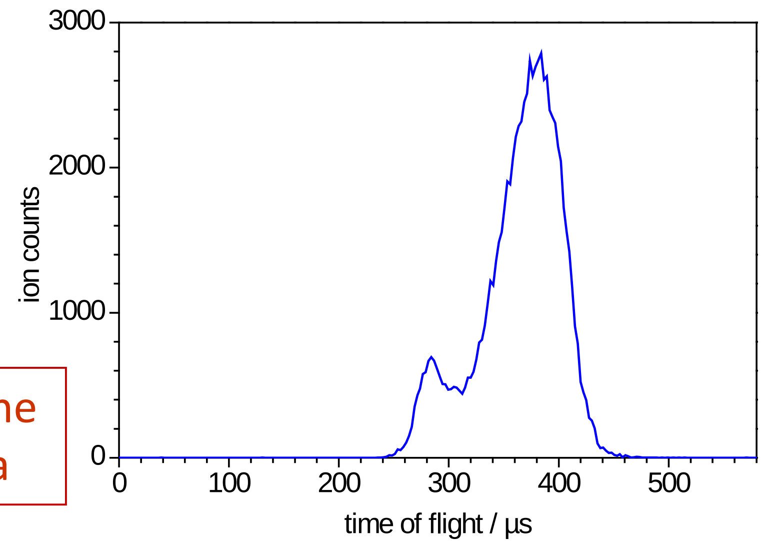




Example taken from ISOLTRAP:
(Stable) ^{85}Rb, 900ms excitation duration)

mean ToF ← Time-of-Flight spectrum

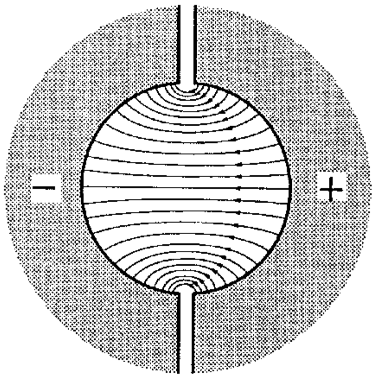




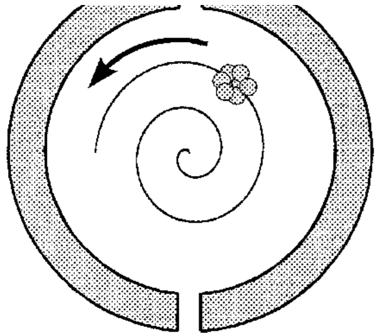
Example taken from ISOLTRAP:
(Stable) ^{85}Rb, 900ms excitation duration)

Penning trap, radial modes (cyclotron/magnetron motion)

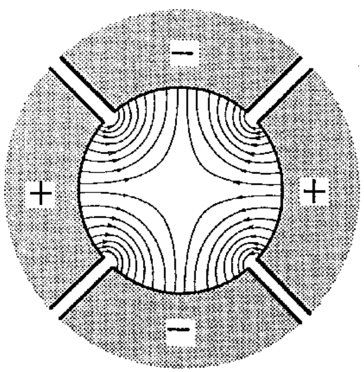
dipolar excitation



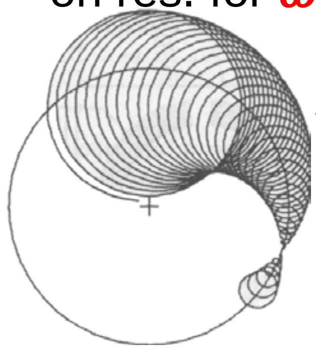
resonances at $\boldsymbol{\omega_+}$ and, used here, $\boldsymbol{\omega_-}$



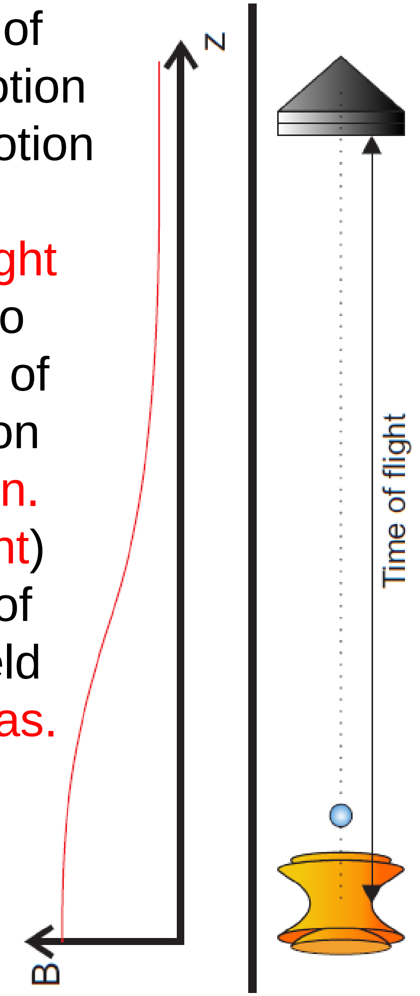
quadrupolar excitation



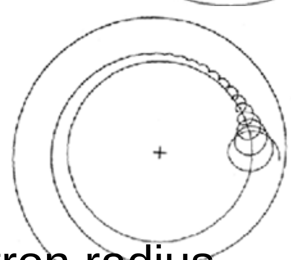
conversion to and fro on res. for $\boldsymbol{\omega_c = \frac{qB}{m}}$

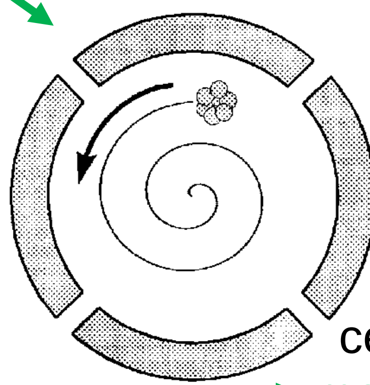


conversion of magnetron motion to cyclotron motion detected by time-of-flight effect due to acceleration of circulating ion (orbital magn. dipol moment) in gradient of magnetic field => mass meas.



damping by buffer gas

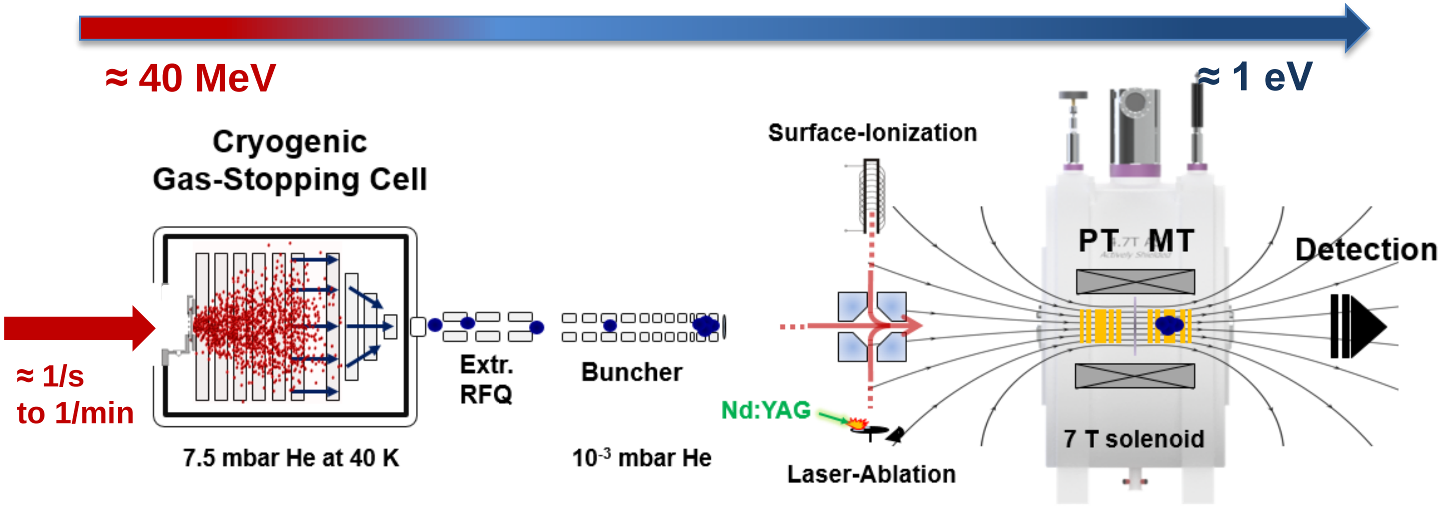


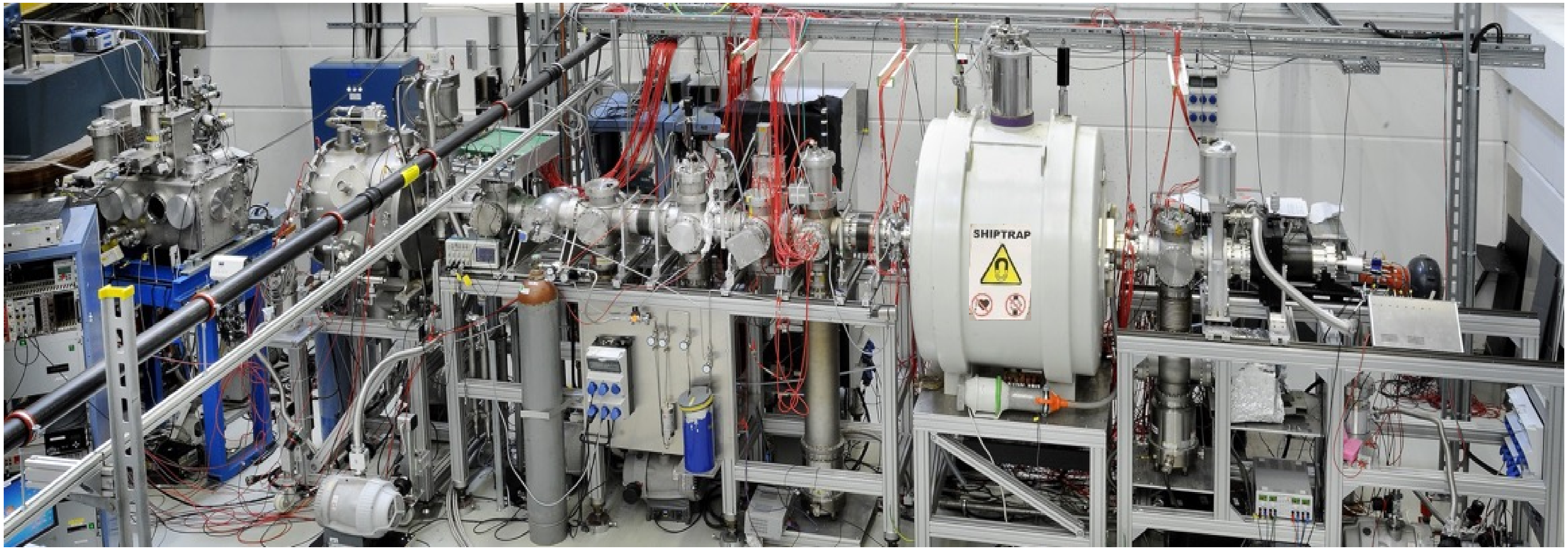


centering at resonance => mass selection

decrease of cyclotron radius
increase (!) of magnetron radius

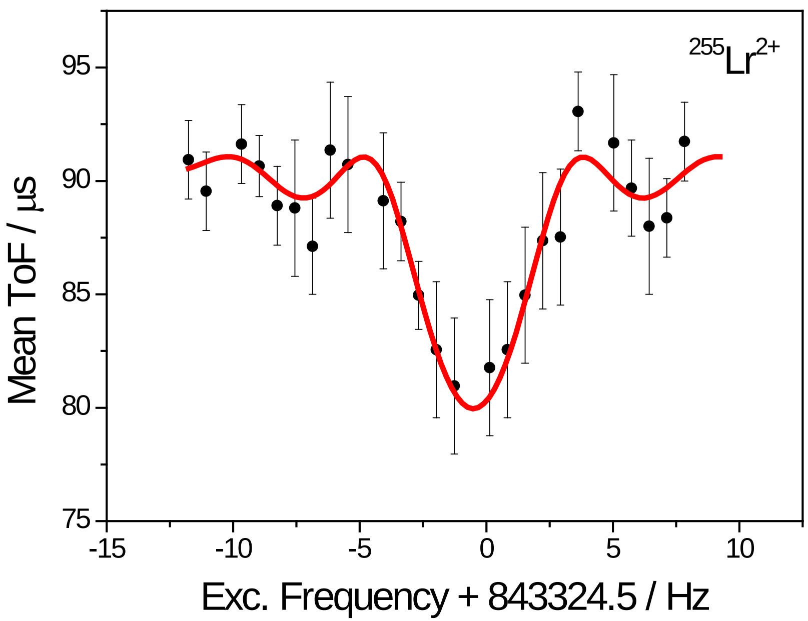
SHIPTRAP at GSI (Darmstadt/Germany)

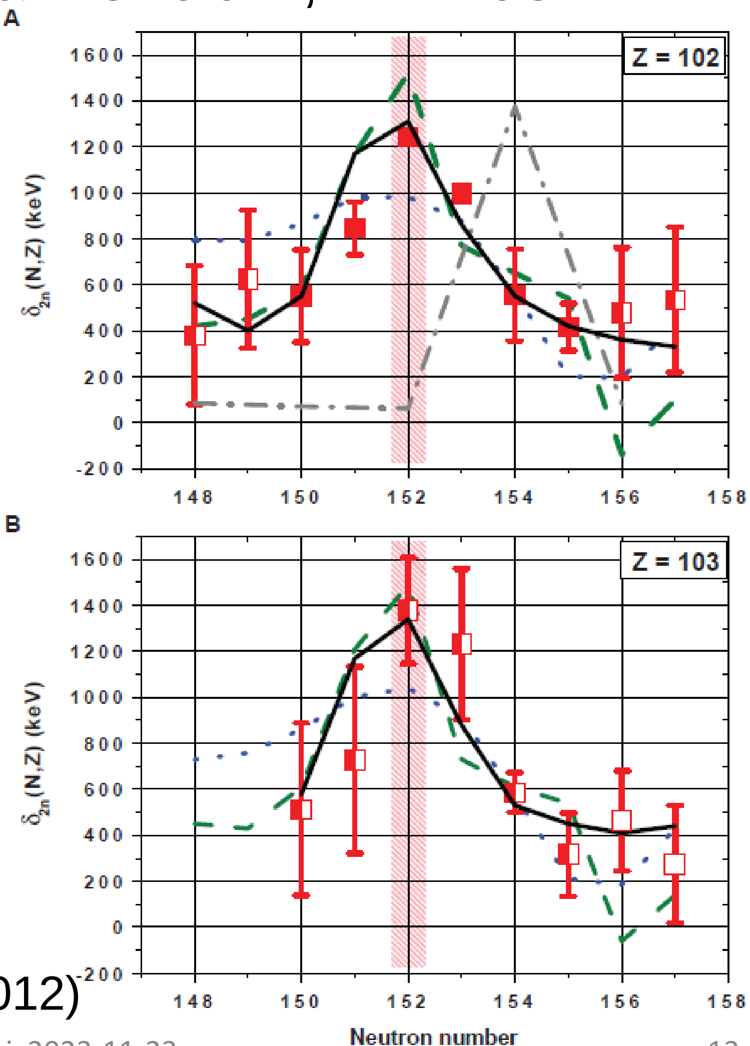




Earlier SHIPTRAP Measurements

First Direct Mass Measurements above Uranium
Direct Mapping of Nuclear Shell Effects
Here for Nobelium, *Z* = 102, and Lawrencium, *Z* = 103

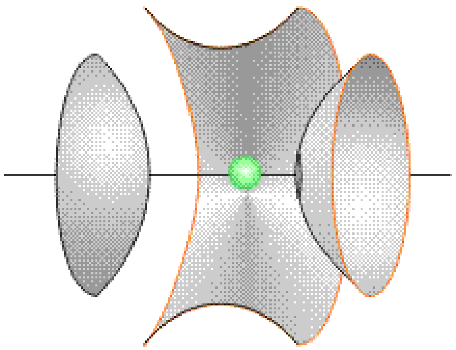




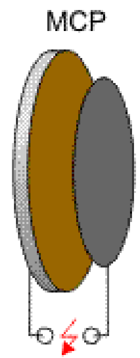
Production yield of ^{256}Lr
just 2 nuclei/minute
(at about 40 MeV kinetic energy!)

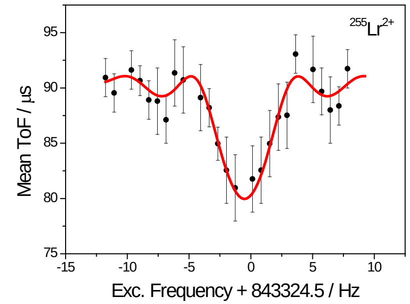
M. Block *et al.*, Nature 463, 785 (2010)
E. Minaya Ramirez *et al.*, Science 337, 1207 (2012)

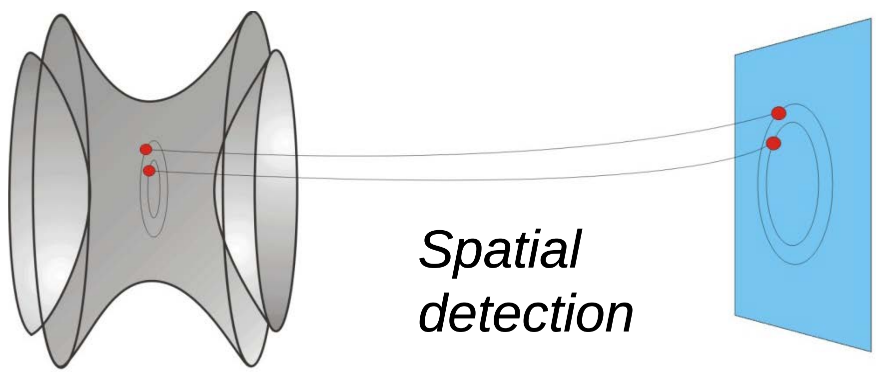
Principle of Phase-Imaging Ion-Cyclotron-Mass Spectrometry



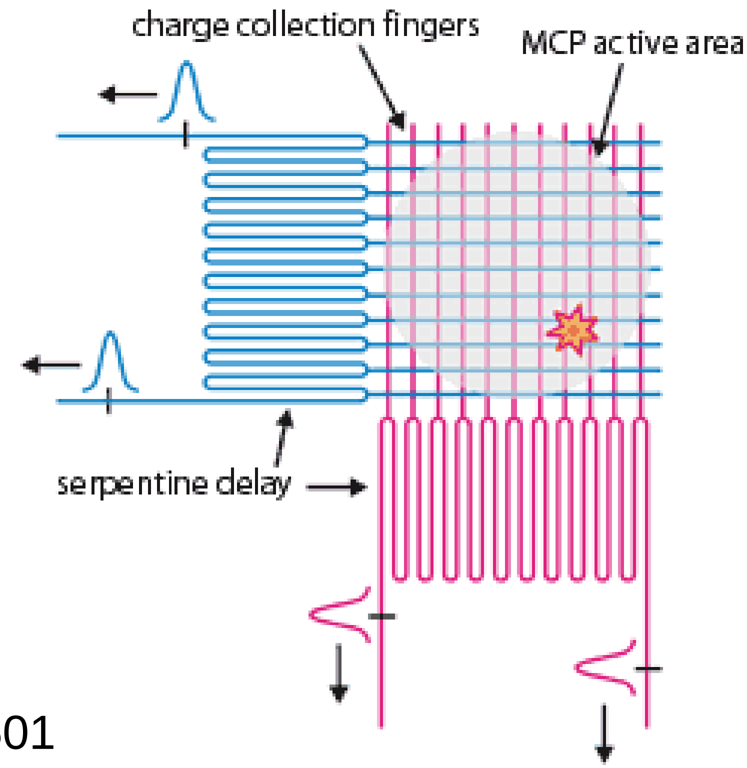
time-of-flight detection



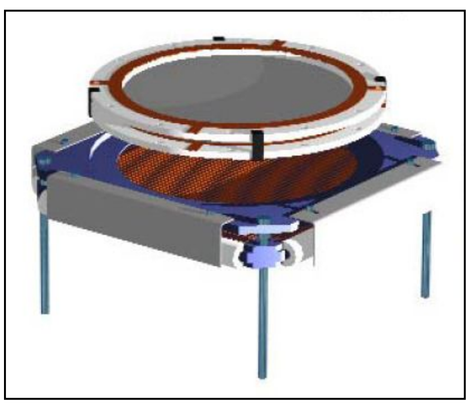




Spatial detection

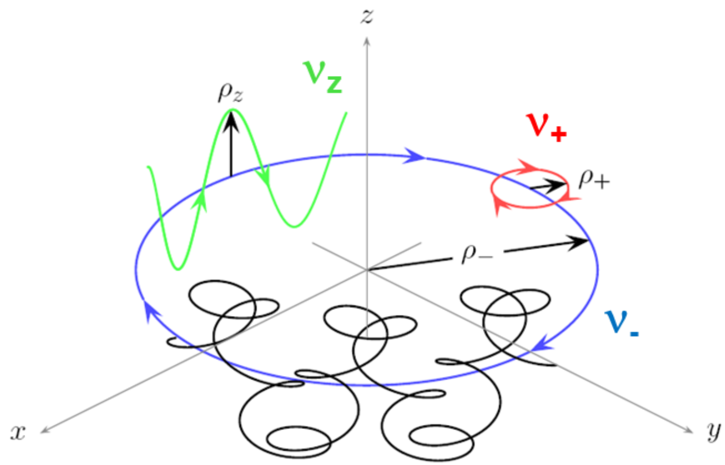


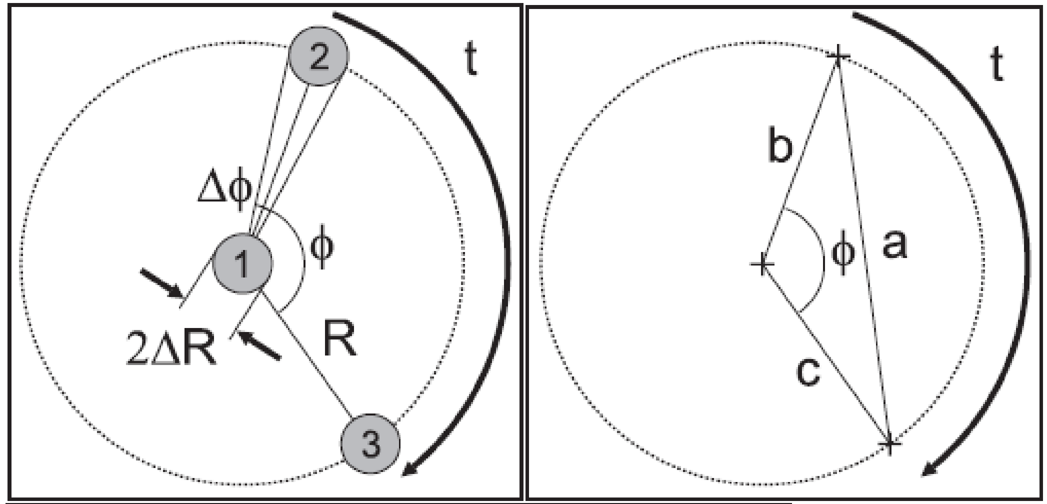
with delay-line detector

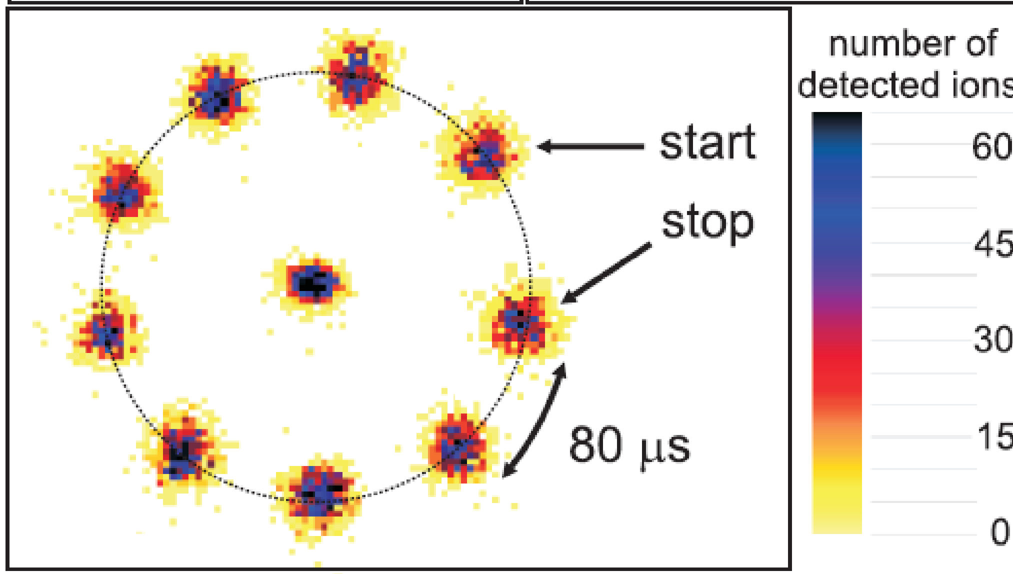


S. Eliseev *et al.*,
PRL 110 (2013) 082501
Appl. Phys. B 114 (2014) 107

Principle of Phase-Imaging Ion-Cyclotron-Mass Spectrometry



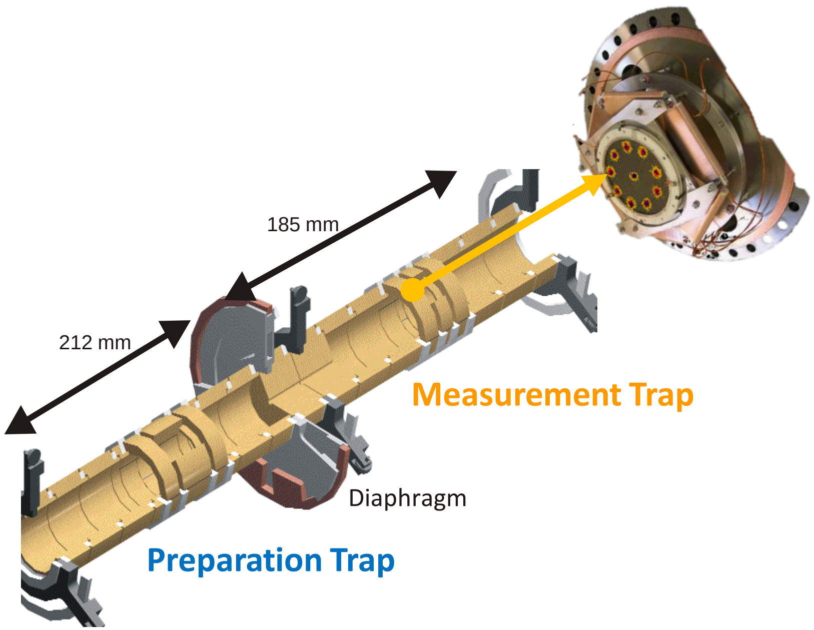


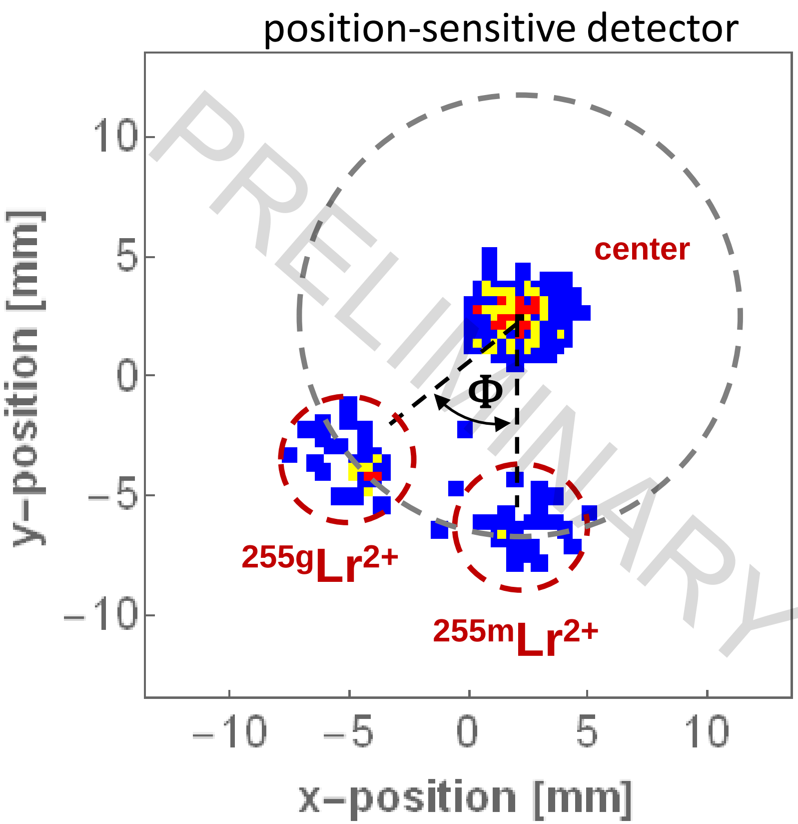


=> Improvement by
a factor 5
    in uncertainty and
a factor 40
    in resolution
or by more than an order of
    magnitude in reduction of
    measurement time

S. Eliseev *et al.*,
PRL 110 (2013) 082501
Appl. Phys. B 114 (2014) 107

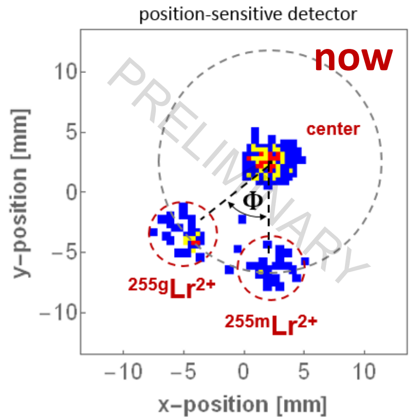
PI-ICR application at SHIPTRAP for mass meas. of ^{255}Lr (Z=103)



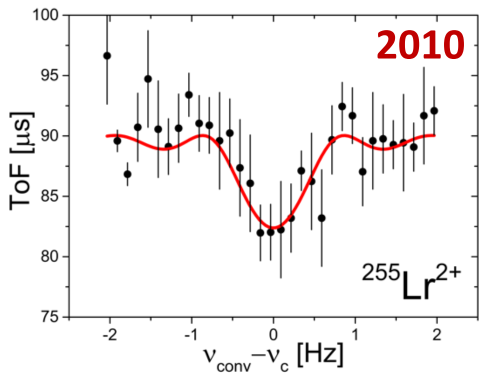


- 10 hour data file, 1200 ms acc. time
- **mass resolving power m/Dm ≈ 10^7**

PI-ICR application at SHIPTRAP for mass meas. of ^{255}Lr (Z=103)



vs.



	Detected Ion Rate (norm.)	Mass Resolving Power R	Accuracy (stat.)	„Exposure“ Time
now	≈ 14/h	≈ 10.000.000	≈ 4 E-9	≈ 10 h
	CryoCell	**PI-ICR technique** **+ improved magnetic field stab.** **+ low-noise trap power supplies**		
2010	≈ 2/h	≈ 1.000.000	≈ 1 E-7	≈ 30 h

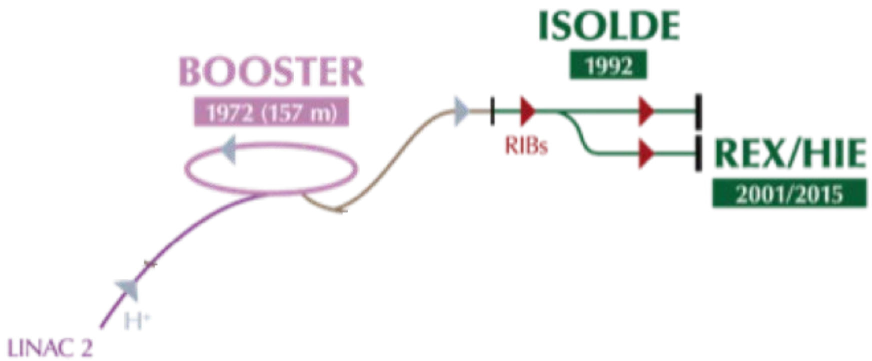
15 times more precise in ⅓ of the time

+ ISOMER resolved

ISOLDE at CERN

- Isotope Separator OnLine Device

- Produces Radioactive Ion Beams (RIBs)
- Approved by the CERN council in 1964
  - Initially used 600-MeV protons from SC
  - Then used 1.0-GeV (later 1.4-GeV) protons from the PSB
- ~0.1% of the CERN budget
- ~7% of the CERN scientists
- ~50% of the CERN protons



ISOLTRAP/CERN first steps — precision MS for nuclear physics

Hyperfine Interactions 38 (1987) 793

FIRST ABSOLUTE MASS MEASUREMENTS OF SHORT-LIVED ISOTOPES

G. BOLLEN, P. DABKIEWICZ *, P. EGELHOF, T. HILBERATH, H. KALINOWSKY, F. KERN, H. SCHNATZ, L. SCHWEIKHARD and H. STOLZENBERG

Institut für Physik, Universität Mainz, Mainz, Fed. Rep.

R.B. MOORE

Foster Radiation Laboratory, McGill University, Montre

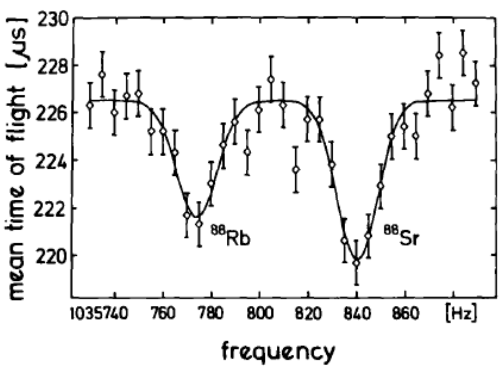
H.-J. KLUGE

CERN, Geneva, Switzerland
and
Institut für Physik, Universität Mainz, Mainz, Fed. Rep.

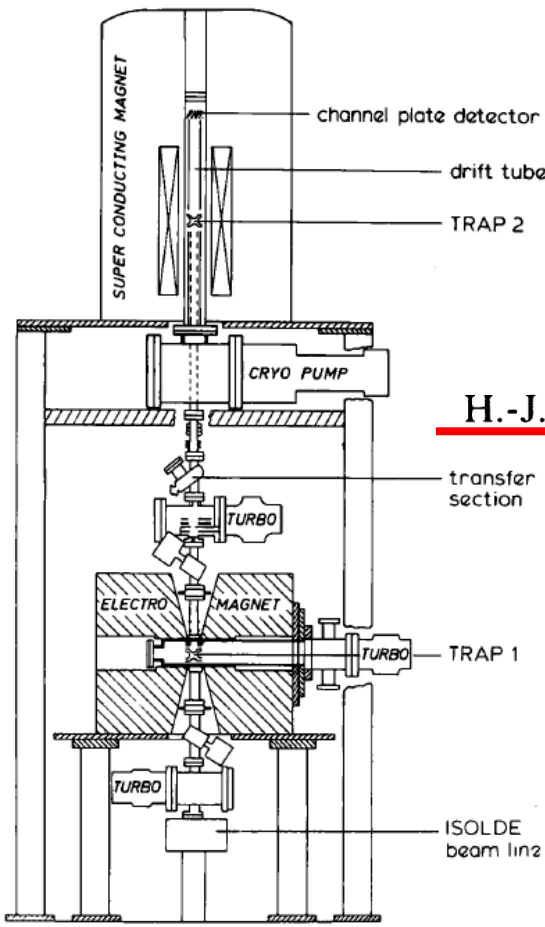
G.M. TEMMER **, G. ULM ***
and
THE ISOLDE COLLABORATION

CERN, Geneva, Switzerland

Absolute mass measurements of short-lived isotopes have been performed at the on-line mass separator ISOLDE at CERN by determining the cyclotron frequencies of ions confined in a Penning trap. The cyclotron frequencies for ^{77,78,85,86,88}Rb and ^{88}Sr ions could be determined with a resolving power of 3×10^5 and an accuracy of better than 10^{-6}, which corresponds to 100 keV for mass $A=100$. The shortest-lived isotope under investigation was ^{77}Rb with a half-life of 3.7 min. The resonances obtained for the isobars ^{88}Rb and ^{88}Sr were clearly resolved.



^{88}Rb vs. ^{88}Sr



At that time ISOLDE was
fed by the Synchro-Cyclotron
ISOLTRAP then moved along
with ISOLDE and
was further developed …

17 DECEMBER 1990
PHYSICAL REVIEW LETTERS

H. Stolzenberg, St. Becker, G. Bollen, F. Kern,
H.-J. Kluge, Th. Otto, G. Savard, and L. Schweikhard
G. Audi
R. B. Moore

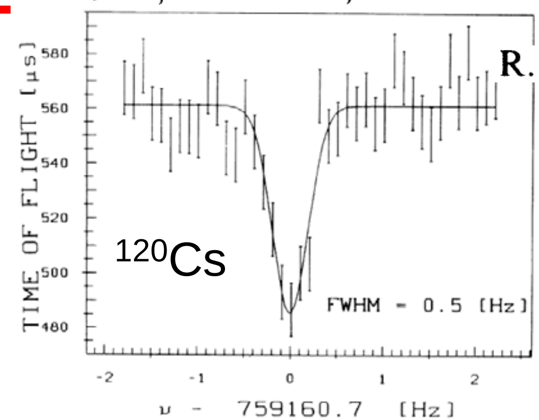
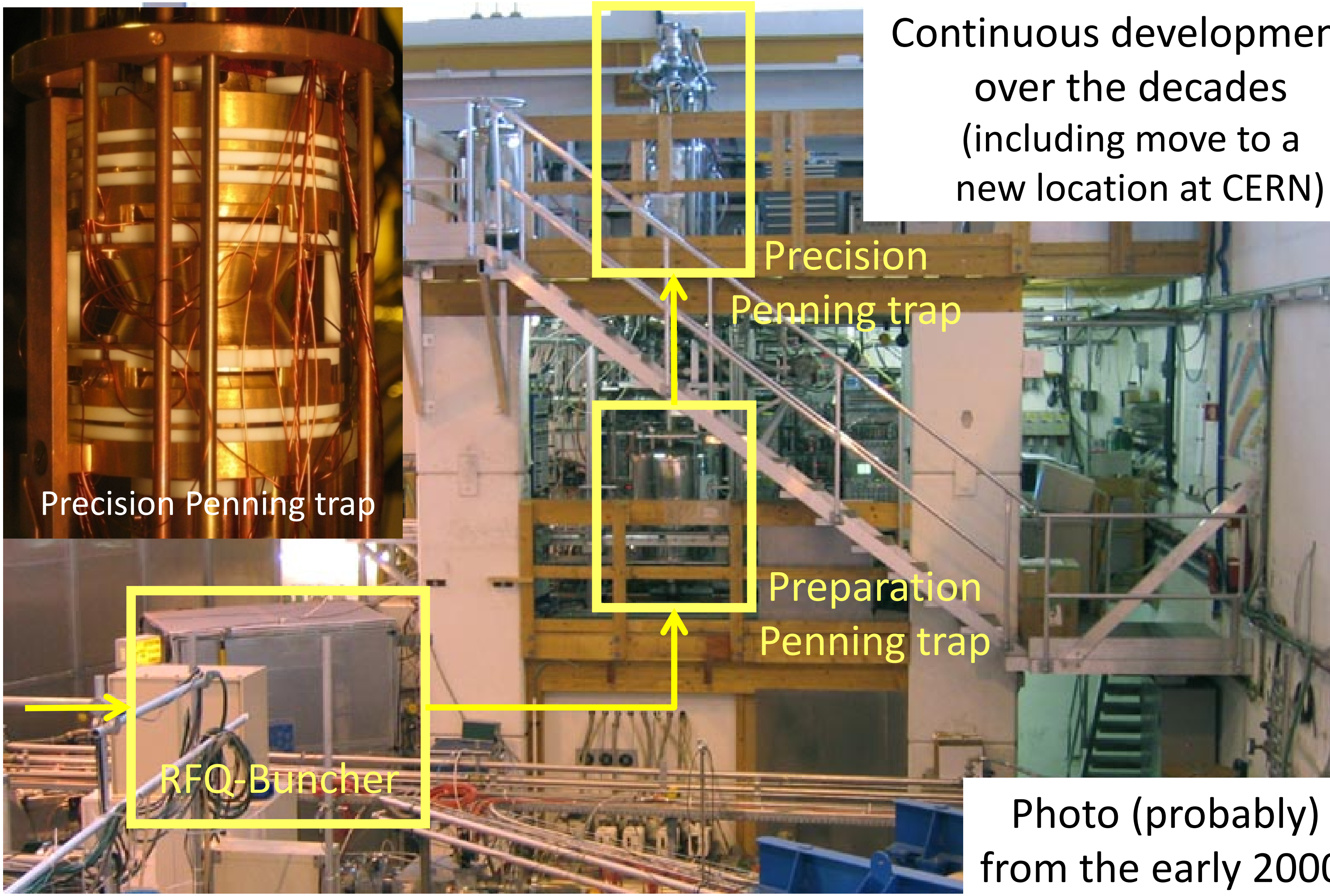


FIG. 2. Cyclotron resonance of ^{120}Cs ($T_{1/2}=64$ s). A resolving power of 1 500 000 is obtained.

ISOLTRAP at ISOLDE/CERN



Continuous developments over the decades (including move to a new location at CERN)

Photo (probably) from the early 2000s

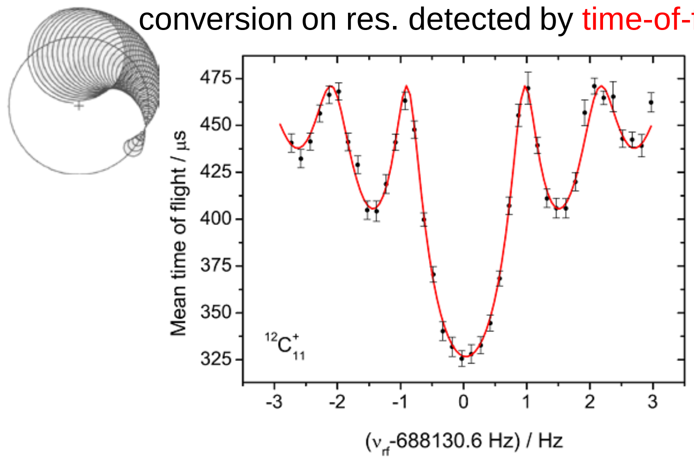
ISOLTRAP at ISOLDE/CERN

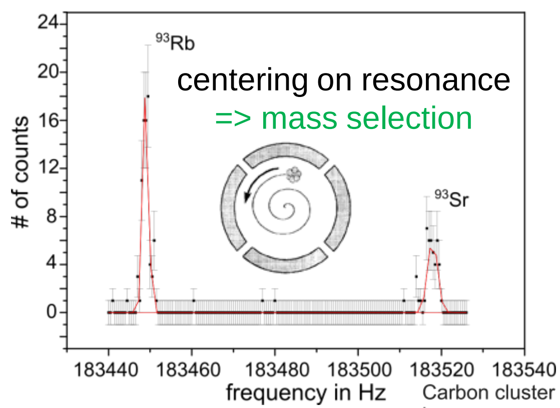
ISOLDE/CERN delivers a
- **continuous ion beam**
  => (1) RFQ buncher
- **of a mixture of isobaric species**
  => (2) Preparation Penning trap

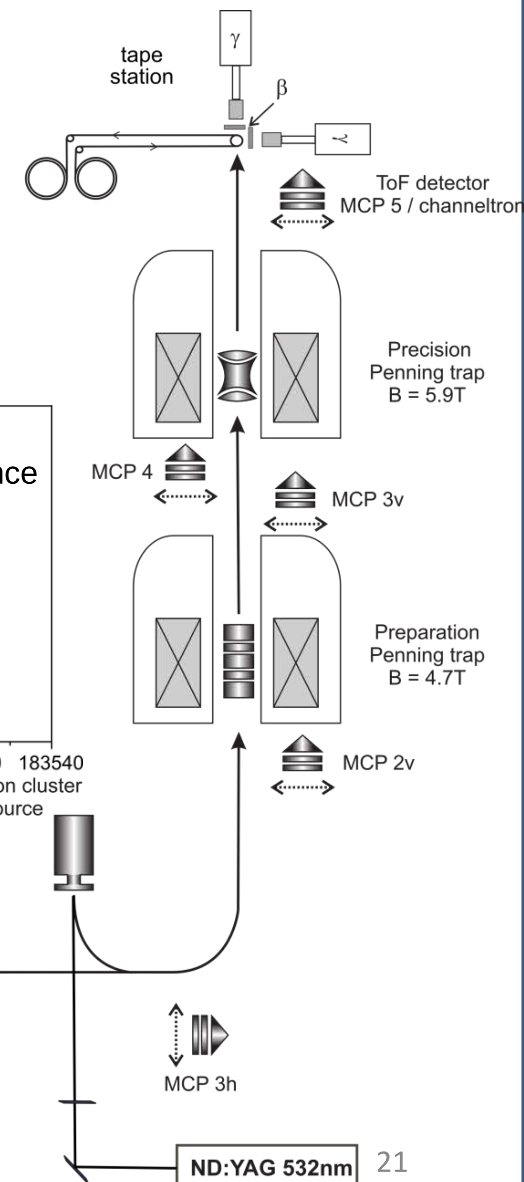
before forwarding for MS at the
- **Measurement Penning trap**

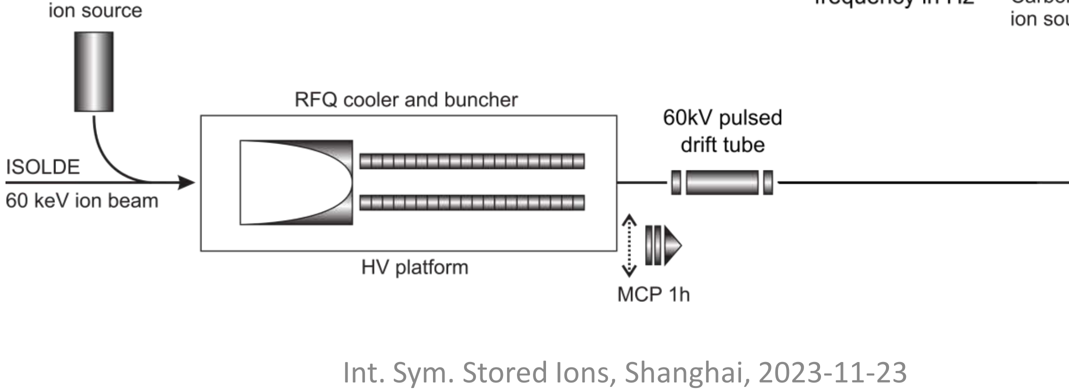
=> Triple-Trap System

conversion on res. detected by time-of-flight effect for mass meas.



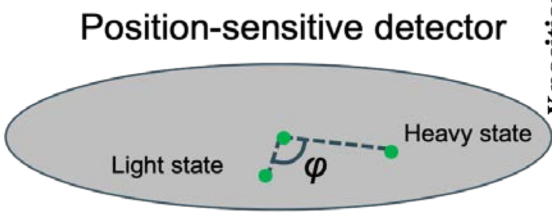


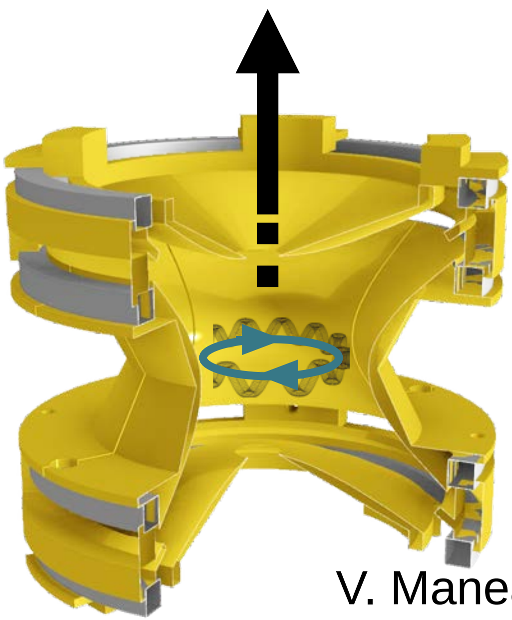


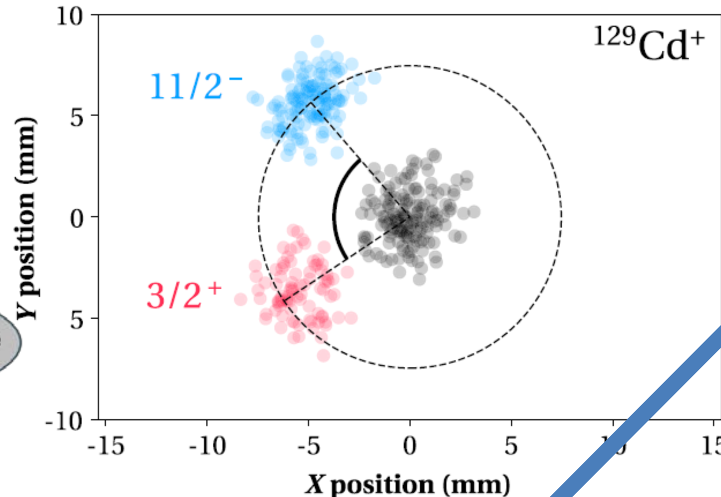


Example of a PI-ICR (and MR-ToF) application at ISOLTRAP

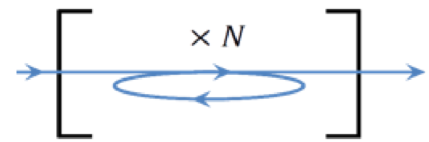
Isomer resolving of cadmium-129

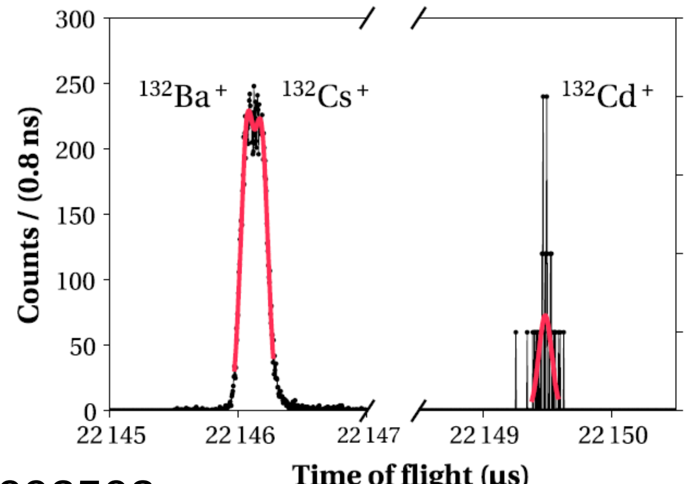






MR-ToF MS Electrost. Ion Beam Trap





V. Manea *et al.*, PRL 124 (2020) 092502:

First glimpse of the N = 82 shell closure below Z = 50 from new masses of cadmium isotopes and isomers

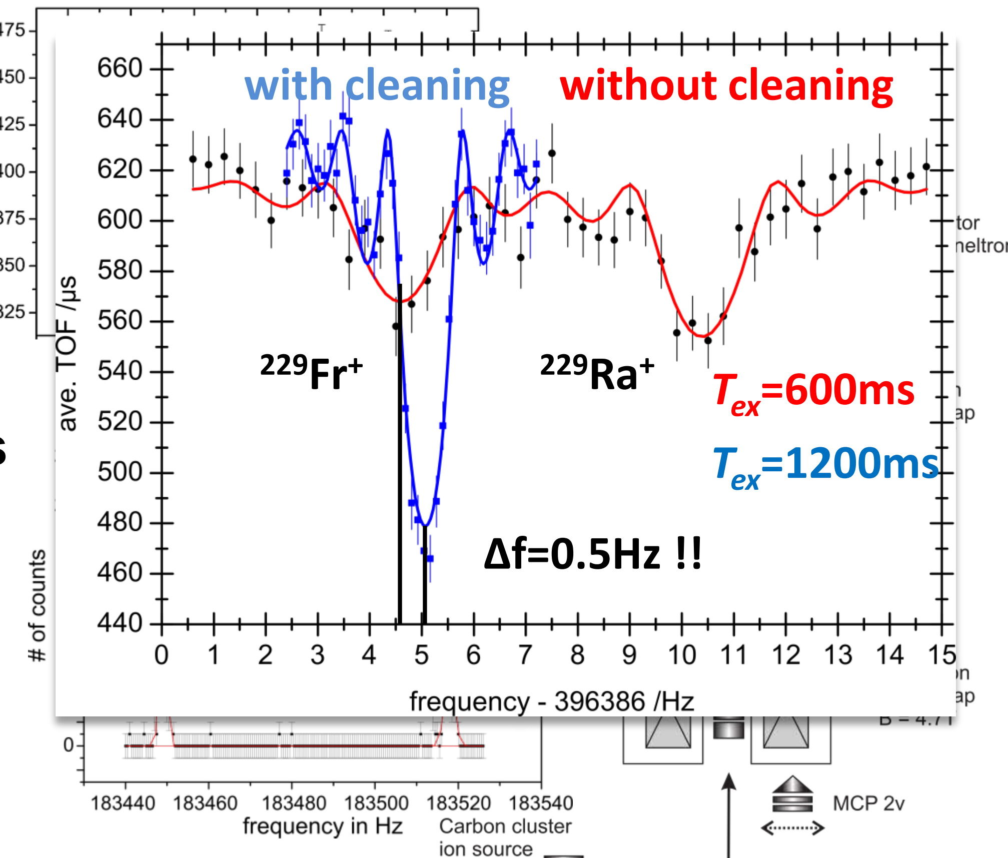
ISOLDE/CERN delivers a

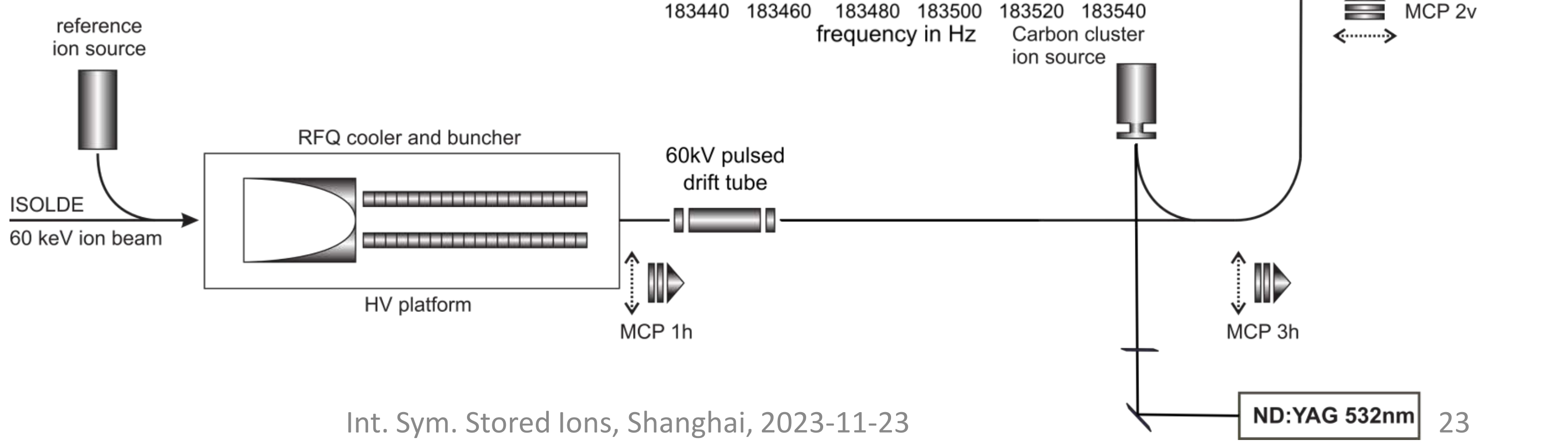
- **continuous ion beam**
  => (1) RFQ buncher
- **of a mixture of isobaric species**
  => (2) Preparation Penning trap

before forwarding for MS at the

- **Measurement Penning trap**

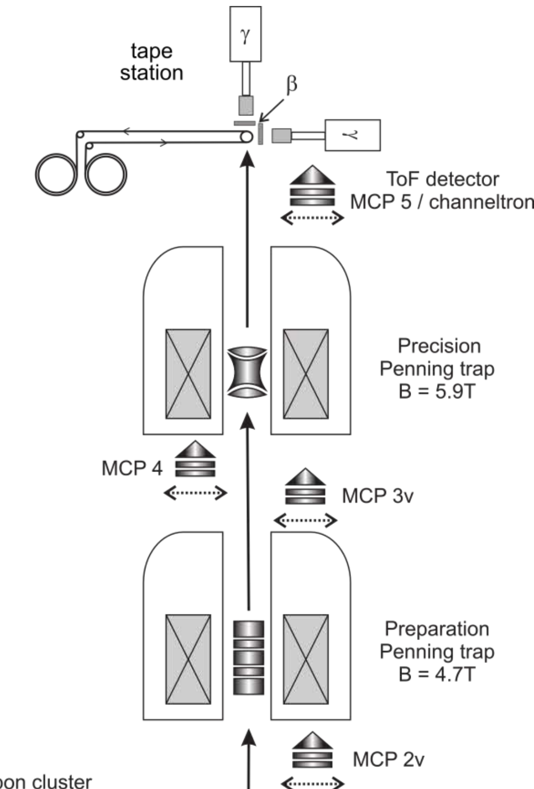
=> **Triple-Trap System**

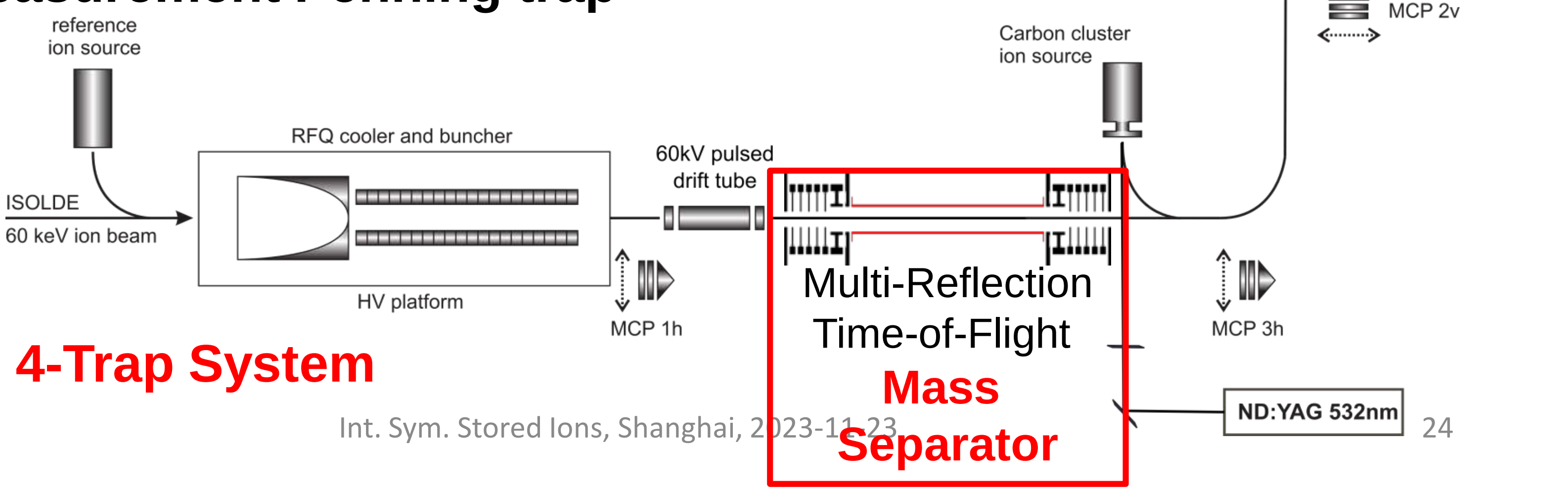




ISOLDE/CERN delivers a
- **continuous ion beam**
  => (1) RFQ buncher
- **of a mixture of isobaric species**
  => (2) MR-ToF MS
- **Centering**
  => (3) Preparation Penning trap

before forwarding for MS at the
- **=> (4) Measurement Penning trap**

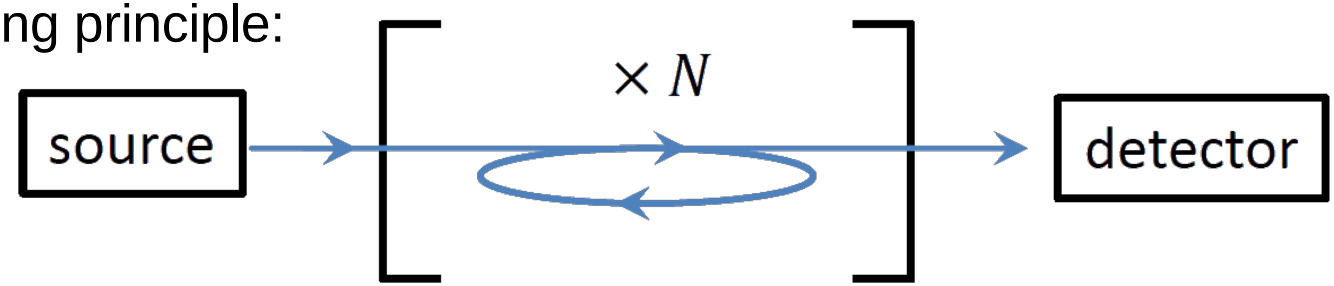




=> unique 4-Trap System

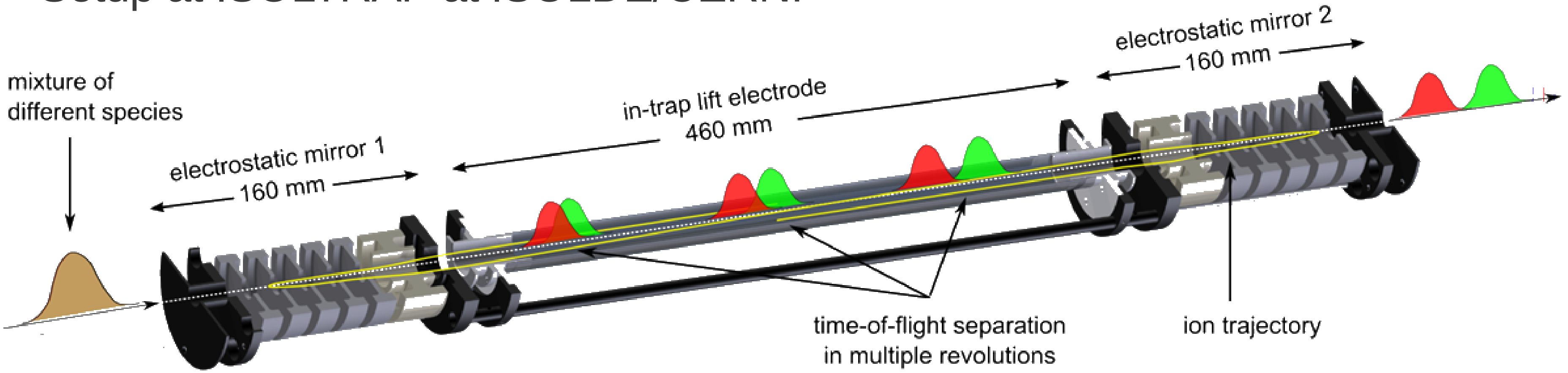
Multi-Reflection Time-of-Flight Mass Spectrometer

MR-ToF working principle:



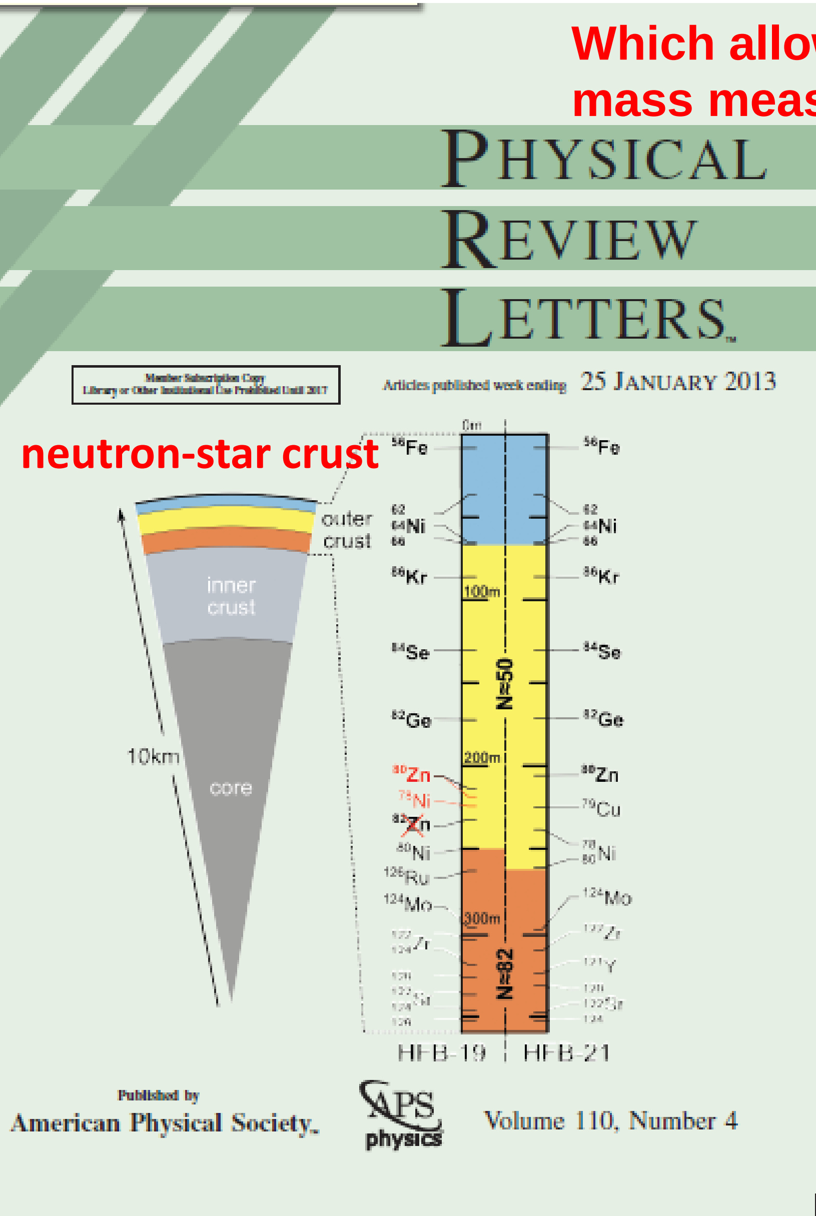
Electrostatic Ion Beam Trap (EIBT)

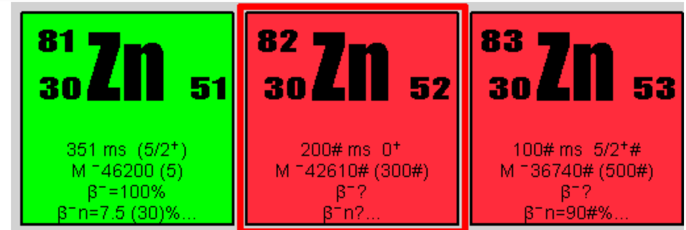
Setup at ISOLTRAP at ISOLDE/CERN:

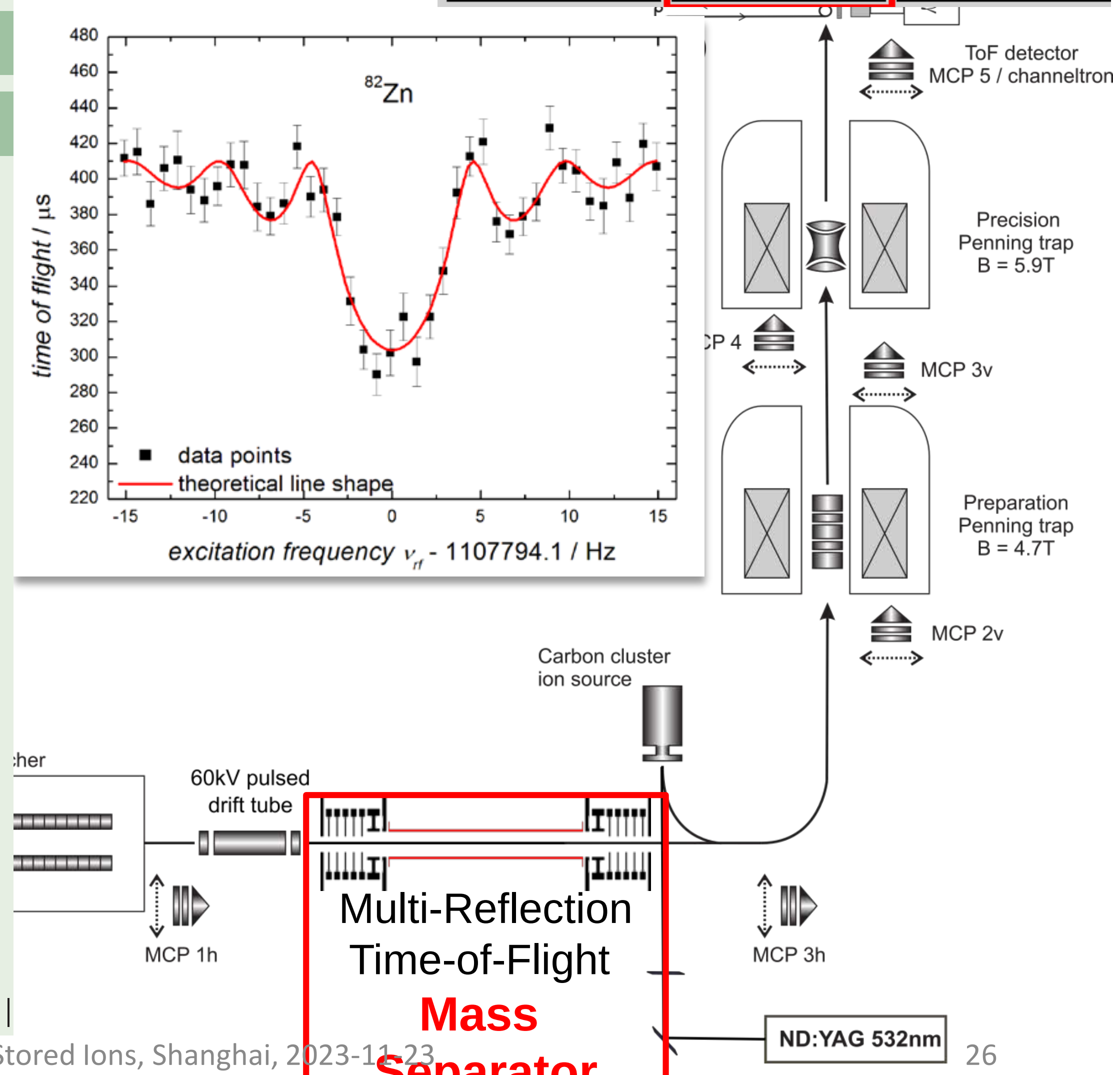


R.N. Wolf *et al.*, Hyperfine Interact 199 (2011) 114
Int. J. Mass Spectrom. 313 (2012) 8
Nucl. Instrum. Meth. A 686 (2012) 82
Int. J. Mass Spectrom. 349-350 (2013) 123

Which allowed a precision mass measurement of Zn-82

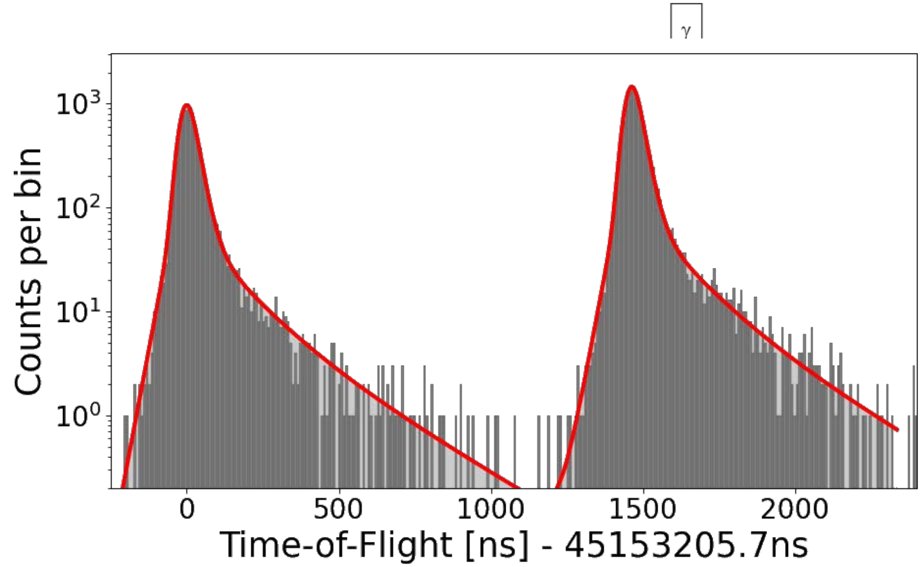




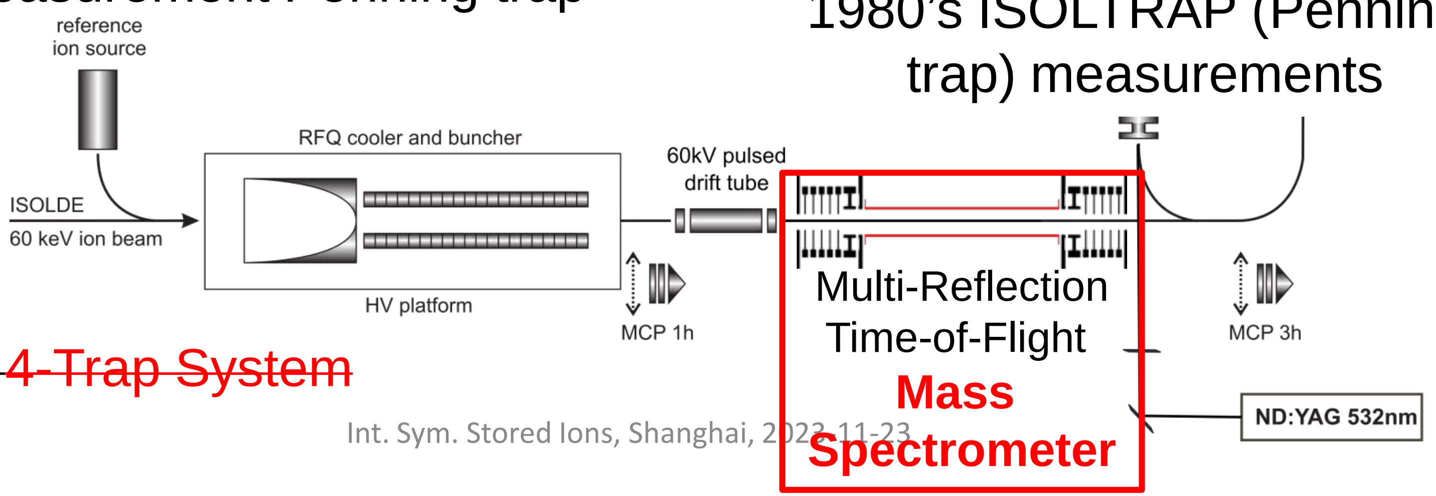


Multi-Reflection Time-of-Flight Mass Separator

ISOLDE/CERN delivers a
- **continuous ion beam**
  => (1) RFQ buncher
- **of a mixture of isobaric species**
  => (2) **MR-ToF MS**
- ~~Centering~~
  ~~=> (3) Preparation Penning trap~~
~~before forwarding for MS at the~~
- ~~=> (4) Measurement Penning trap~~

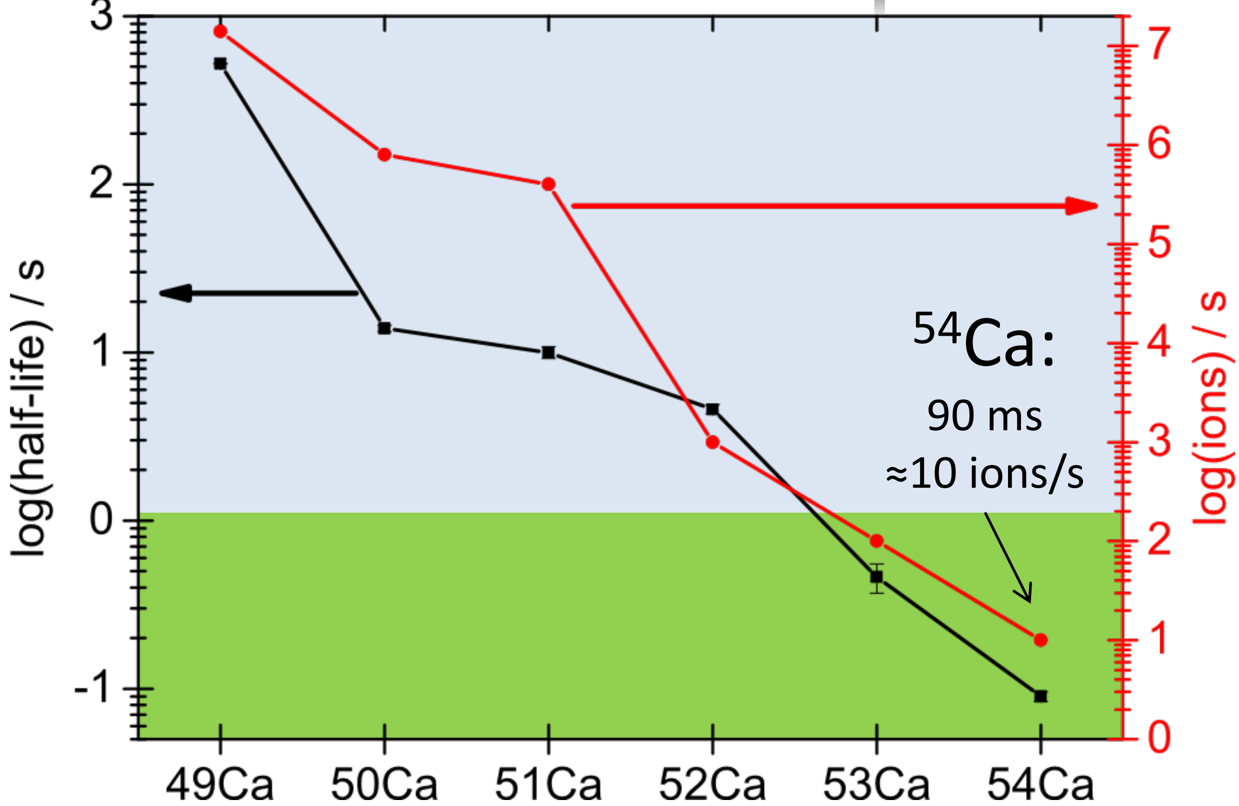


^{88}Sr vs. ^{88}Rb with
Higher resolving power than 1980's ISOLTRAP (Penning-trap) measurements

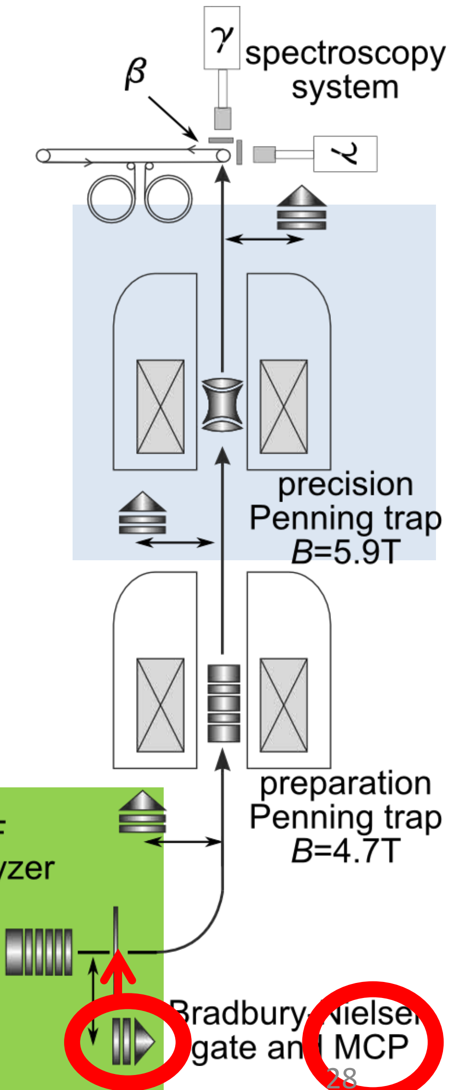
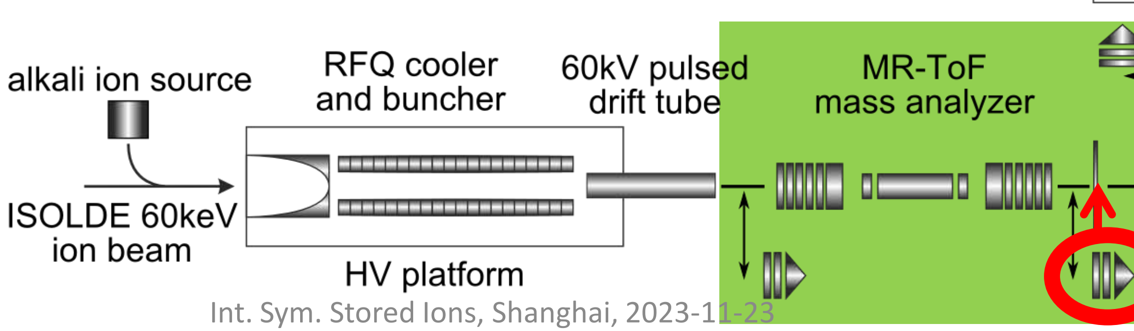


~~=> unique 4-Trap System~~

MR-ToF mass spectrometer: n-rich Ca isotopes

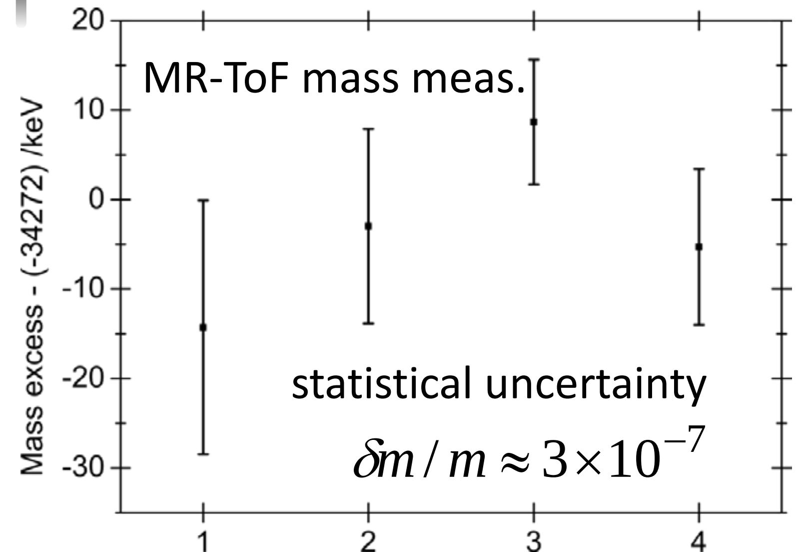


Multi-Reflection Time-of-Flight **Mass Spectrometer**

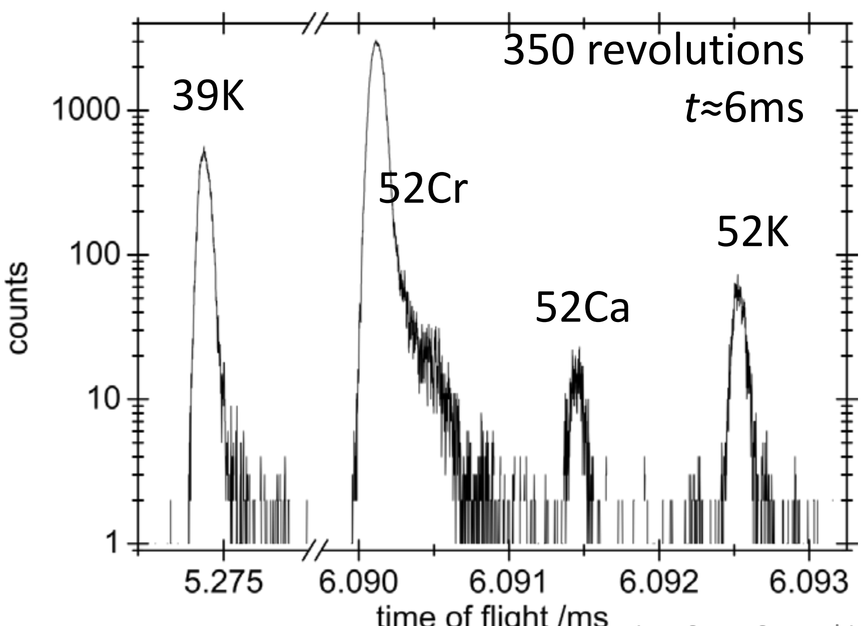



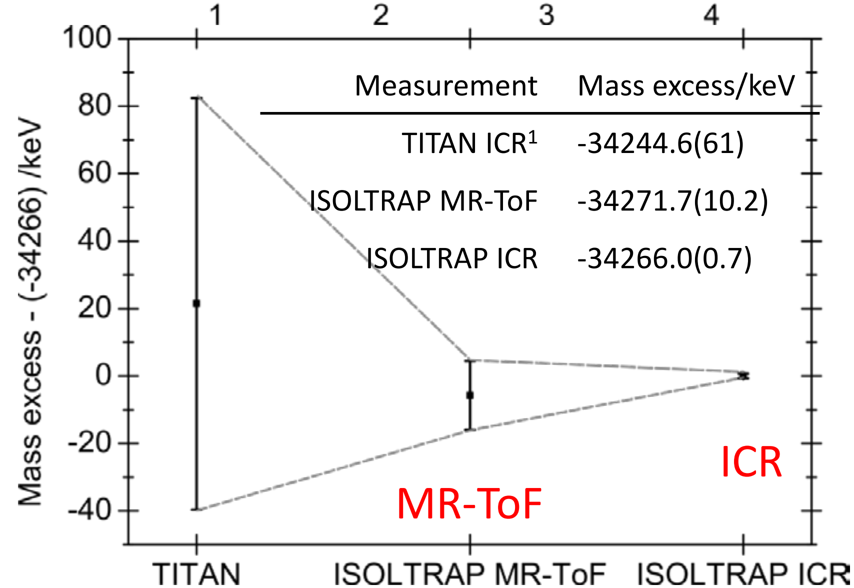
MR-ToF mass spectrometer: n-rich Ca isotopes

- TITAN/TRIUMF measurements of ^{51,52}Ca
  Gallant *et al.*, PRL 109, 032506 (2012)
- ISOLTRAP measurement agrees with TITAN
- ^{51,52}Ca measured with Penning trap
- ^{52,53,54}Ca measured with MR-ToF-MS
  - ➔ MR-ToF MS agrees with PT measurements
  - ➔ sub-ppm statistical mass uncertainty



MR-ToF spectrum

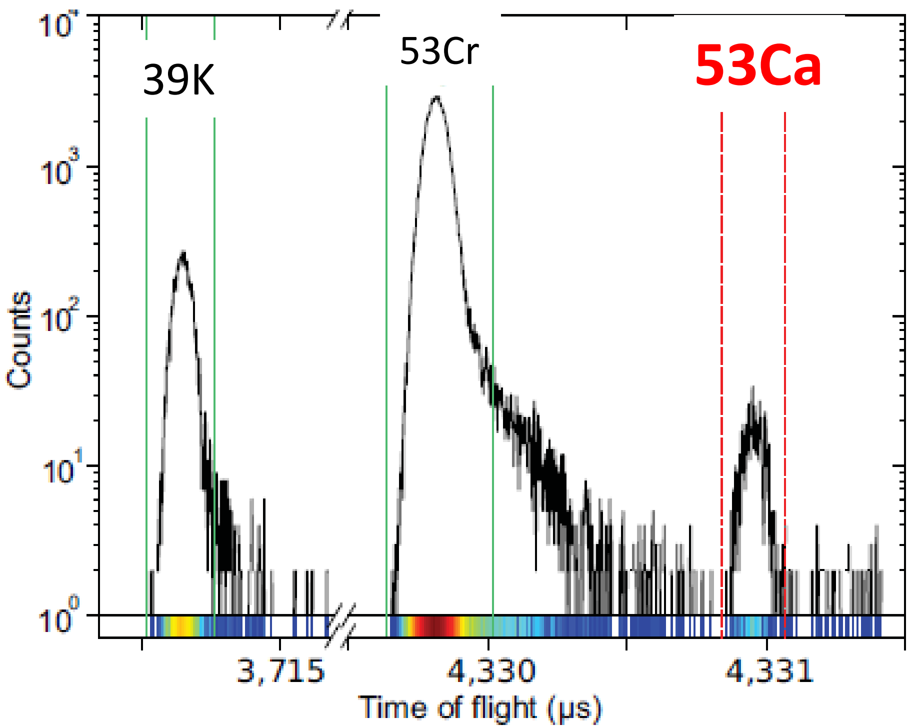




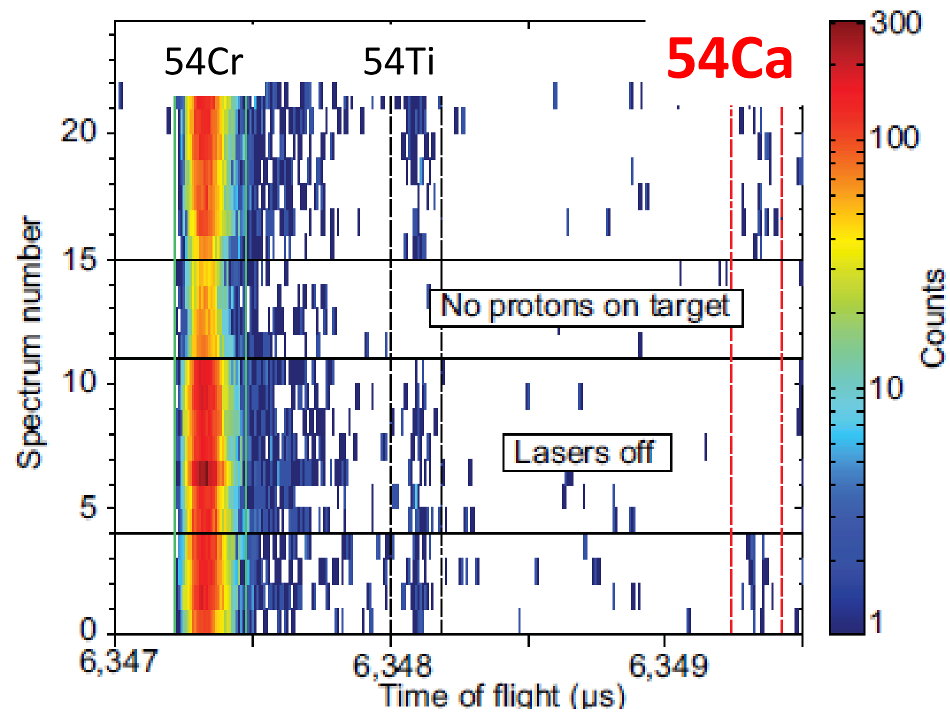
MR-ToF mass spectrometer: n-rich Ca isotopes *N*=32

Z=20 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55

***A*=53:** measurement cycle ≈ 4ms



***A*=54:** measurement cycle ≈ 6ms



6413 counts in 12.6h
$t_{1/2}$ = 500ms

➔ 9 counts/minute

2314 counts in 18.2h
$t_{1/2}$ = 90ms

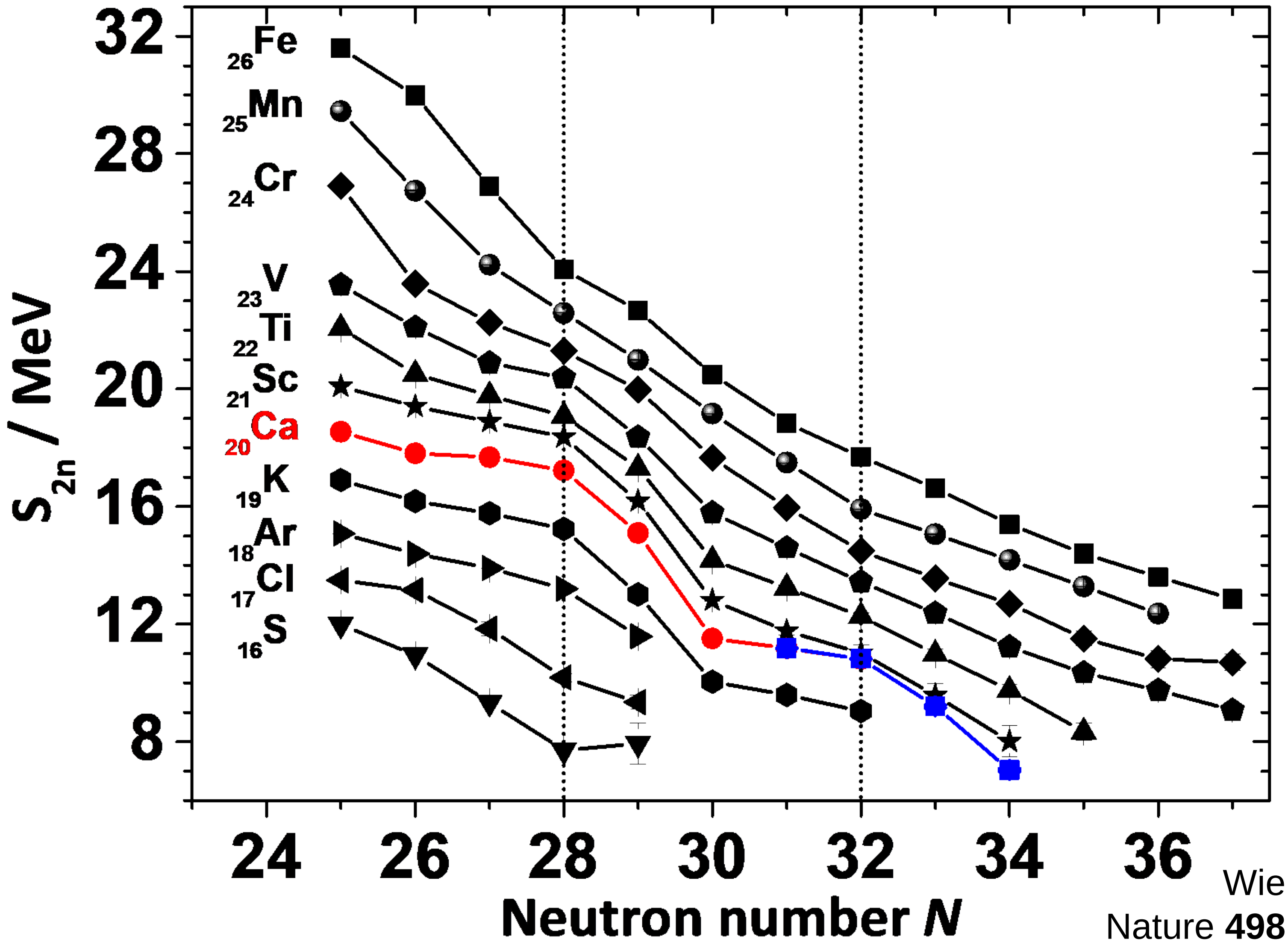
➔ 2 counts/minute

statistical uncertainty ≈ 45keV ➔ $\delta m/m \approx 9\text{x}10^{-7}$

Wienholtz *et al.*,
Nature 498, 346 (2013)

Results: S_{2n} values (2-neutron separation energy)

Z=20 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55

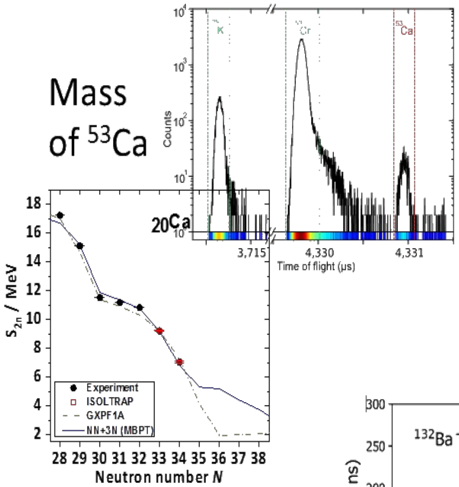


Wienholtz *et al.*, Nature **498,** 346 (2013)

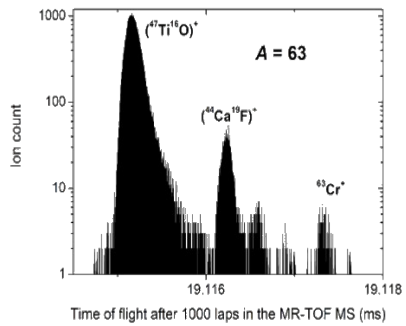
Multi-Reflection Time-of-Flight MS at ISOLTRAP/CERN

Precision mass spectrometry

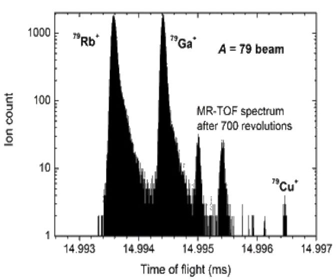
Mass of ^{53}Ca

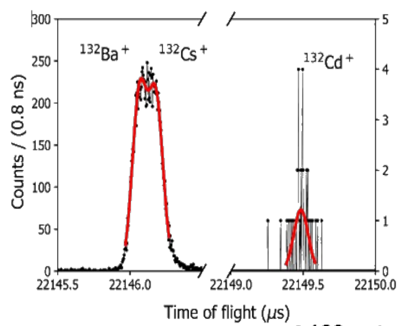


Mass of ^{63}Cr



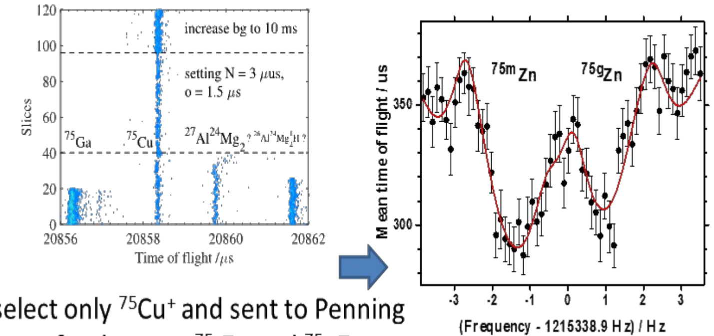
Mass of ^{79}Cu





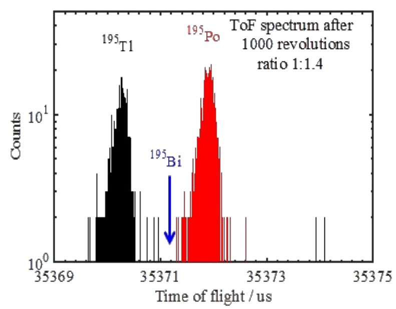
Mass of ^{132}Cd

Mass selection for Penning-trap MS



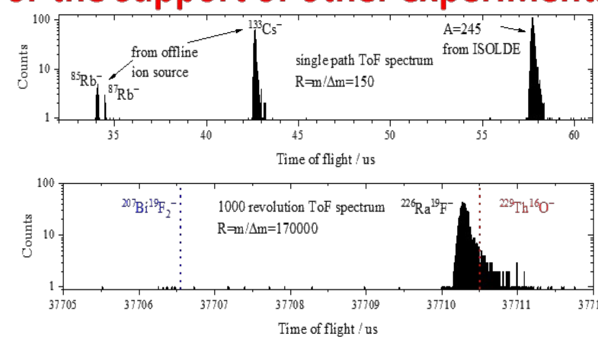
select only $^{75}Cu^{+}$ and sent to Penning traps for decay to ^{75g}Zn and ^{75m}Zn

Mass selection for nuclear decay studies



α-spectroscopy for clean polonium samples

ISOLDE-beam analysis, e.g. for target/ion source developments or the support of other experiments

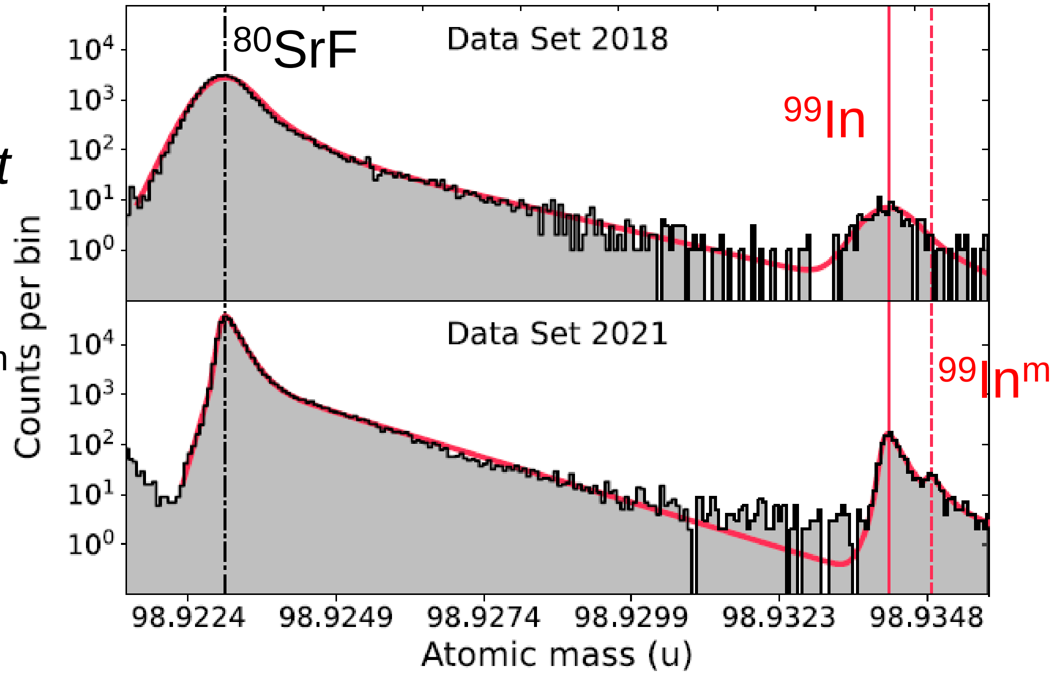


RaF^{+} beam analysis for Collinear Resonance Ionization Spectroscopy (CRIS)

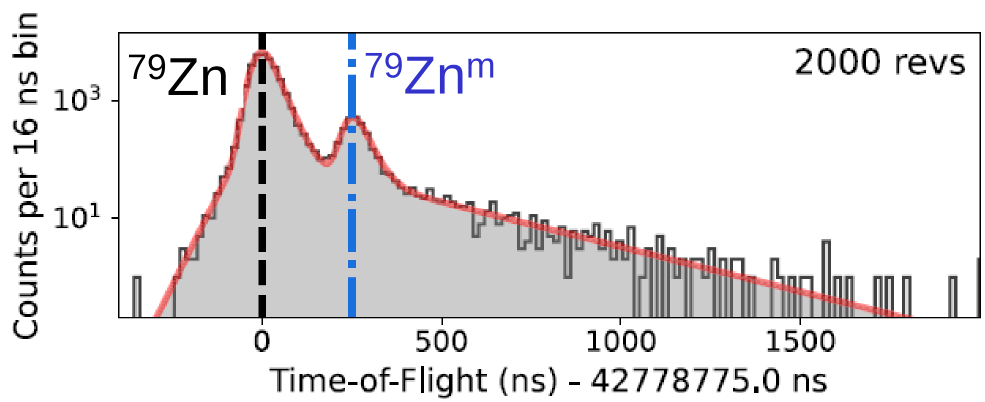
R.N. Wolf *et al.*, PRL 110 (2013) 041101
F. Wienholtz *et al.*, Nature 498 (2013) 346
M. Rosenbusch *et al.*, PRL 114 (2015) 202501
D. Atanasov *et al.*, PRL 115 (2015) 232501
A. Welker *et al.*, PRL 119 (2017) 192502
M. Mougeot *et al.*, PRL 120 (2018) 232501
B. Marsh *et al.*, Nature Phys. 14 (2018) 1163
R.F. Garcia Ruiz *et al.*, Nature 581 (2020) 396
T. Day Goodacre *et al.*, PRL 126 (2021) 032502
M. Mougeot *et al.*, Nature Phys. 17 (2021) 1099
L. Nies *et al.*, PRL 131 (2023) 022502
G. Cubiss *et al.*, PRL 131 (2023) 202501
L. Nies *et al.*, PRL 131 (2023) 222503

Mass measurements of $^{99-101}$In challenge ab initio nuclear theory of the nuclide ^{100}Sn, M. Mougeot *et al.*, Nature Phys. 17, 1099 (2021)

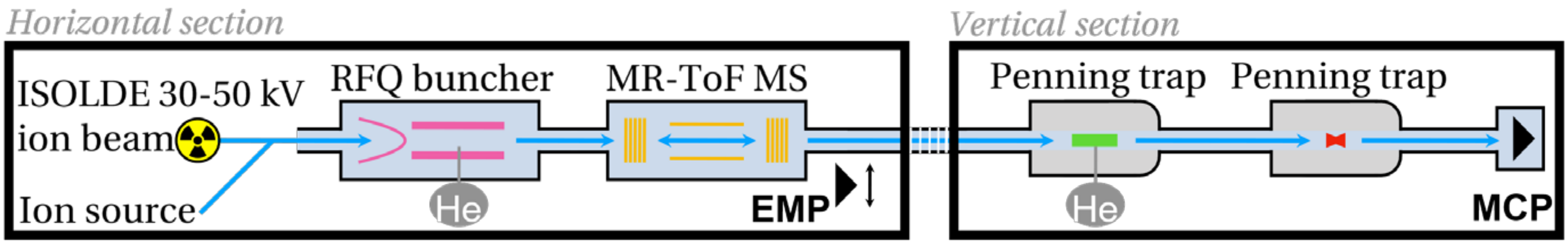
Isomeric excitation energy for ^{99}In^{m} from mass spectrometry reveals contant trend next to doubly magic ^{100}Sn, L. Nies *et al.*, PRL 131, 022502 (2023)



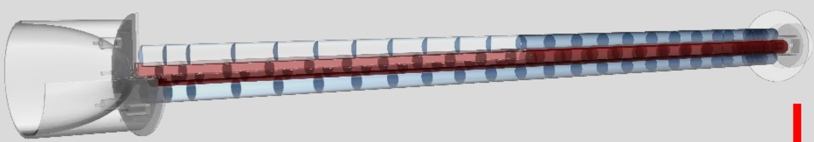
Further Evidence for Shape Coexistence in ^{79}Zn^{m} Near Doubly-Magic ^{78}Ni, L. Nies *et al.*, PRL 131, 222503 (2023)



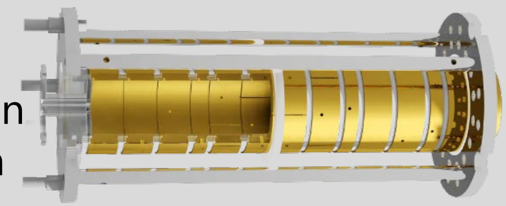
Overview of trapping components



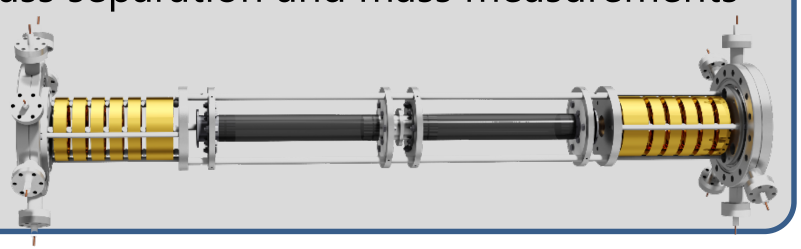
Linear Paul Trap (RFQ buncher)
Cooling and Bunching



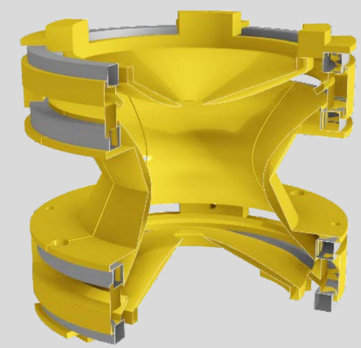
Preparation Penning Trap
Beam preparation and purification



Multi-Reflection Time-of-Flight Mass Spectrometer
Mass separation and mass measurements



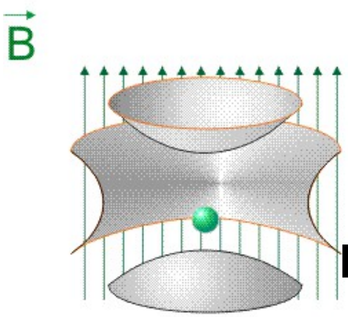
Precision Penning Trap
Mass measurements



Ion trap based mass measurements of short-lived nuclei at ISOLTRAP and SHIPTRAP

Lutz Schweikhard
Inst. of Physics, Univ. of Greifswald
https://physik.uni-greifswald.de/ag-schweikhard/

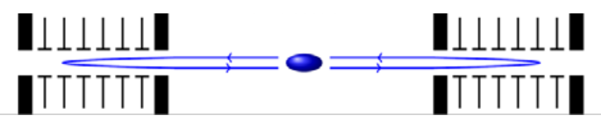
for the
ISOLTRAP and SHIPTRAP collaborations



Penning-trap and

Time-of-Flight

Mass Spectrometry



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at ISOLTRAP (cern.ch) = https://isoltrap.web.cern.ch/
and GSI - SHIPTRAP
= https://www.gsi.de/work/forschung/appamml/atomphysik/anlagen_und_experimente/shiptrap