The use of Traps in Modern Nuclear Physics

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CNRS IN2P3
Les deux infinis

The use of Traps in Modern Nuclear Physics

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- 1997 : PhD at IPN Orsay
    Study of halo nuclei ^{11}Be and ^{11}Li
- 1997-1998 : Post Doctoral position at the NSCL-MSU (US)

Main scientific program :

Study of the modifications of the shell structure in the n-rich nuclei
Experimental program centered around N=20 and N=28

- 1998-2004 : LPC Caen
    Development of the neutron multi-detector array TONNERRE
- 2004-2010 : GANIL
    Scientific coordinator of the LISE spectrometer
- 2010… : CENBG
    Scientific coordinator of the PIPERADE project for DESIR/SPIRAL2

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The use of Traps in Modern Nuclear Physics

Content

- Why to trap particles ?
- What is trapping/cooling ?
- History
- Main applications

- How to trap particles ?
- Penning traps
- Paul traps
- cooling

- Traps in the "real" life
  → Some applications in nuclear Physics

Why to trap particles ?

The modern trappers : grown at the Heisenberg's school $\Delta E \cdot \Delta t \geq 1$

High precision implies very long observation time → ***confinement***

Trapping = isolation of particles over a long period of time

For an atomic physicist → Dream : single atom at rest in a free space,
free of uncontrolled perturbation

⇨ almost a reality with traps

Long' observation time:

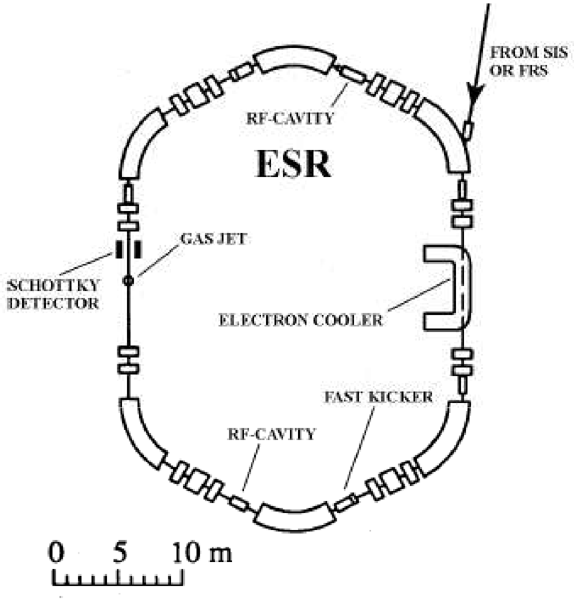
→ ion-motion manipulation;
→ precision measurements ;

Isolation:

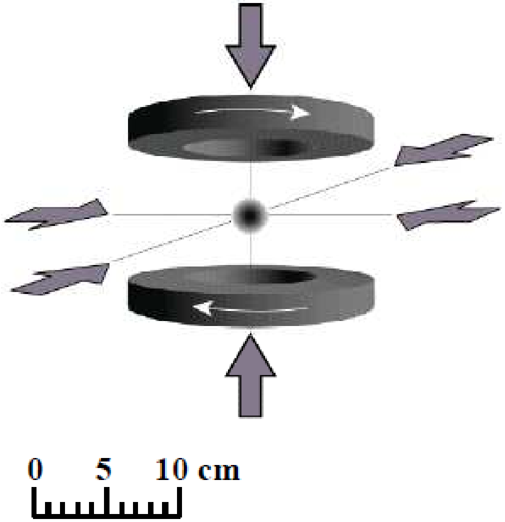
→ no matrix effects → thermal isolation → low temperature
→ high control of transformations (reactions/decays)
→ single species → antiparticles…
→ experiments on few or ever a single ion

Trapping and Storage devices

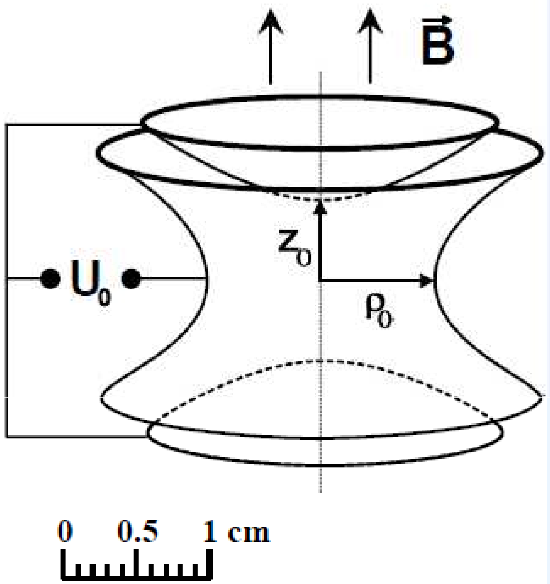
storage ring



Atom trap



Penning and Paul trap



relativistic particles

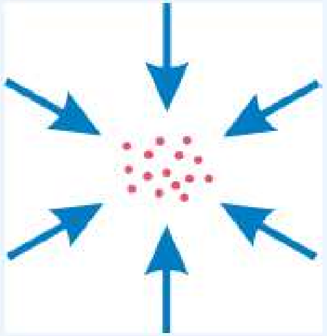
particles at nearly rest in space

- ion cooling
- "infinite" storage time
- single ion sensitivity
- high accuracy
- mass spectrometric capabilities

large number of applications in atomic and nuclear physics

Principle of Trapping

Radial force

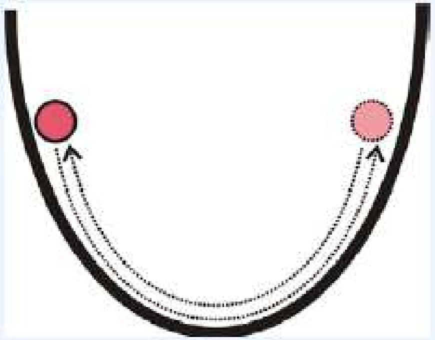


electric fields

magnetic fields

light fields

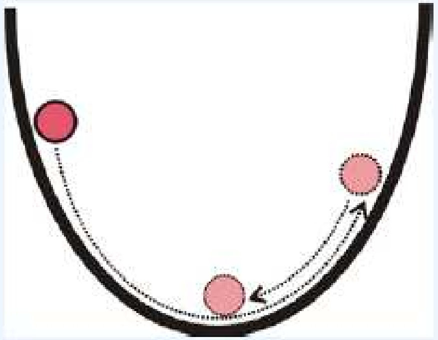
Harmonic potential



harmonic oscillation

2 or 3 independent eigen frequencies

Cooling



damping of oscillation amplitudes

minimization of trap imperfections

“infinite” storage time

History

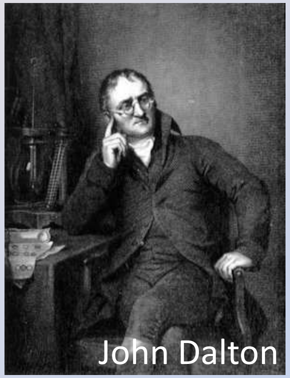
Physics landscape at the dawn of the XXth century

- Mechanical laws → Newton
- Electromagnetism → Maxwell
- Statistical thermodynamics → Kelvin, Maxwell, Boltzman… Gibbs

> *"There is nothing new to be discovered in physics now.*
> *All that remains is more and more precise measurement"*

William Thomson (Lord Kelvin), 1900
British Association for the advancement of Science

Composition of matter



- Matter is made of **indivisible atoms**
- Atoms of a given element are identical
- Atoms of an element can be combined to those of another one to create a chimical compound
- Atoms of different elements have different masses

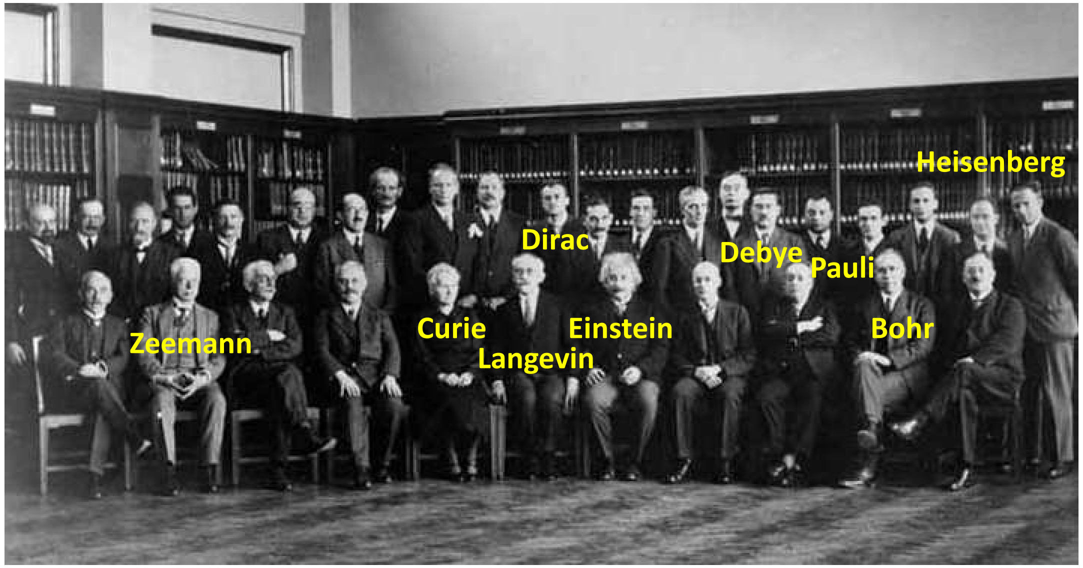

La « boule de billard » de Dalton, 1803

Beginning of XXth century : Two simultaneous revolutions

- Major discoveries → observation of the radioactivity
  → sub-atomic world
- New concepts → Quantum physics

History

- 1924: Pauli proposed the idea of an inner degree of freedom of the electron, which he insisted should be thought of as genuinely quantum mechanical in nature
- 1925: Uhlenbeck&Goudsmit postulate existence of spin and magnetic moment g of the e^-
- 1927: equation of Dirac → theoretical justification of the spin and g=2
- 1927 1930 intense discussions (Dirac, Bohr, Pauli…) about the best experiment to measure the magnetic moment of a free electron
- 1930: Solvay Conference
  "Bohr's theorem" : forbidden tu use "classical" magnetic moment experiments to measure the g-parameter of the free electron



Very interesting period of sciences history. Difficulty to apply the new quantum physics; intellectual "blockage"; problems of "language"…

History

- 1947: First experiment of Nafe, Neson and Rabi on the hyperfine structure of the ground state of H and D atoms

  → difference with theory of 0.2%

  Breit : because of $g \neq 2$

  Other experiments → $g = 2(1.00119 \pm 0.00005)$ $\Delta g/g \sim 5.10^{-5}$

  The uncertainties are coming from relativistic corrections and the interactions between the valence electrons and the other ones in the atom…

- 1948 1957 Better experiments but still on bound electrons in the atom

  → At the limit because the relativistic corrections ~ needed precision

→ Need for new type of experiments on unbound electrons

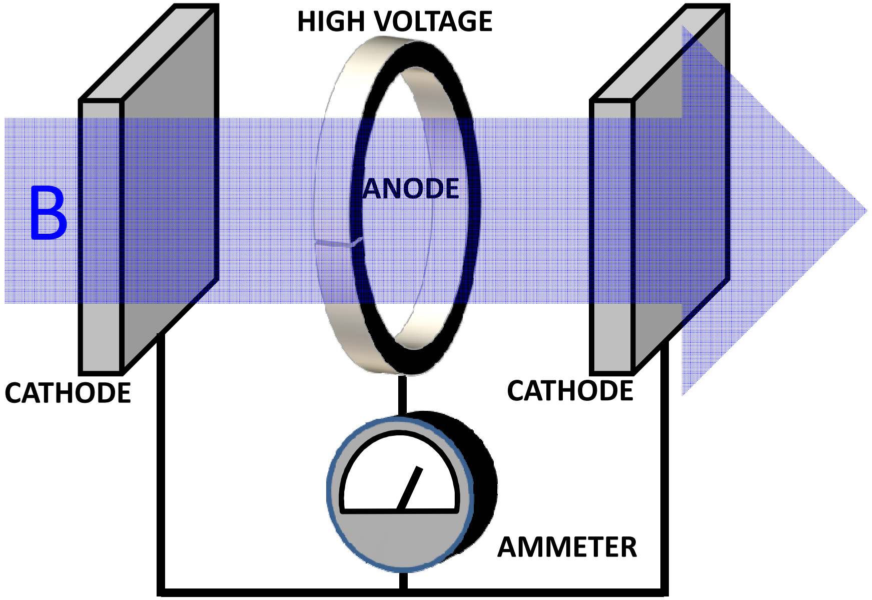
Idea to trap the electrons but…

Impossible to create a 3D trapping potential using only electrostatic fields…

→ Penning and Paul traps

Birth of the Penning trap

1936 : F. M. Penning built a vaccum gauge based on a discharge tube in a magnetic field



-HV between Anode and grounded Cathodes

-Discharges in the gas

→ production of electrons

- Ionization of the gas

→Low current

IDEA : use a magnetic field to force the electrons to describe tight cyclotron orbits around the magnetic field lines

→ slowing the diffusion rate

→ more ionization → more current

Possibility to measure lower pressures

1949 : Pierce → explicit description of a harmonic electron trap

- electric field : pure quadrupolar (hyperbolic electrodes)
- magnetic field

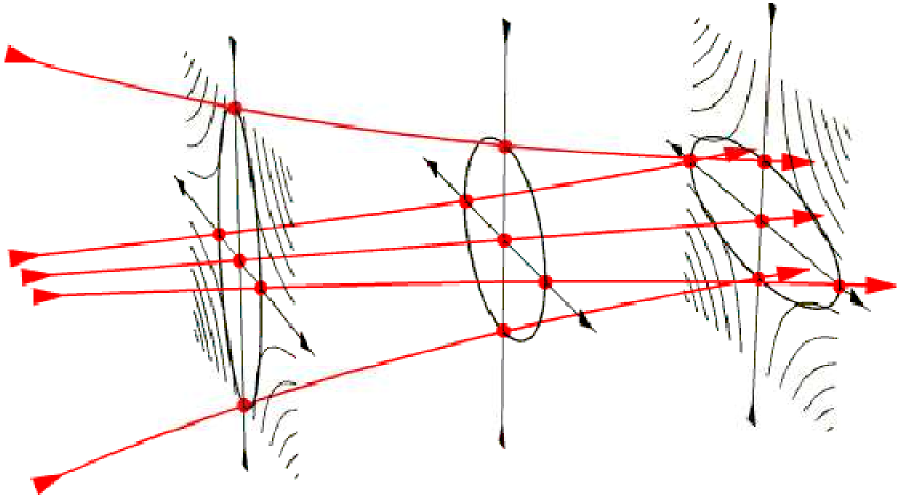
→"Penning-Pierce" trap design

1959 : Dehmelt → first high vaccum magnetron trap – trapping time ~10 sec

Birth of the Paul trap

1951 : W. Paul works on the use of multipoles to focus molecular beams

- Beam along the z axis
- Passage through quadrupoles : If beam focused along x → defocused along y



But if regular sequence of alternatively converging and diverging lenses

→ net convergence : "strong focussing principle"

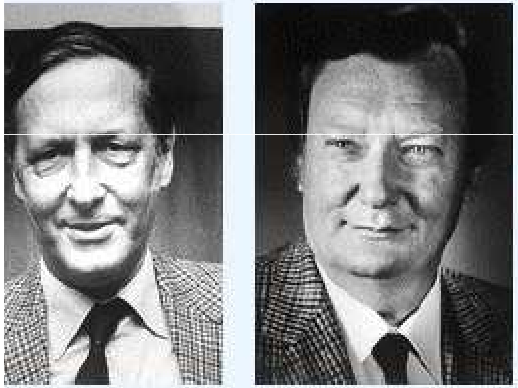
Idea to apply an oscillating field to focus
in x and y direction using the same electrodes

1964 : First application of Paul trap : spectroscopy of Be ions

Pioneers of trapping and cooling

Principle of Penning Traps

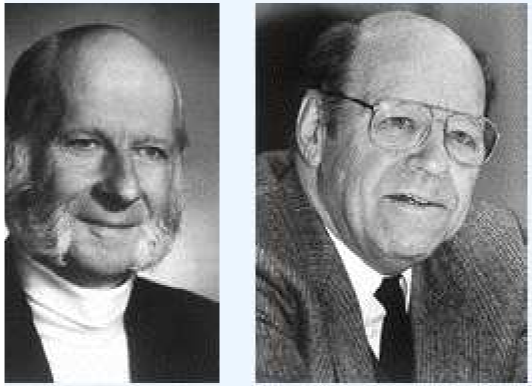
Frans Michel Penning



Storage and Cooling of Antiprotons

Nobel Prize 1984

J. van der Meer
C. Rubbia



Storage and Cooling of Ions

Nobel Prize 1989

H. Dehmelt
W. Paul

Storage and Cooling of Atoms

Nobel Prize 1997

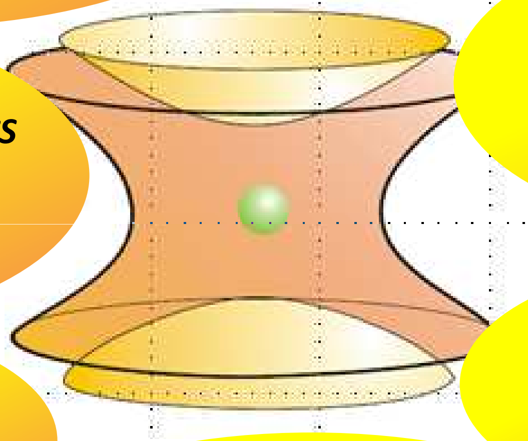
S. Chu C. Cohen-Tannoudji W. D. Phillips

Bose-Einstein Condensation

Nobel Prize 2001

E. Cornell W. Ketterle C. Wieman

Main applications of Ion storage devices



NUCLEAR PHYSICS

nuclear binding energies

laser spectroscopy

decay spectroscopy

CHEMISTRY

TEST OF FUNDAMENTAL INTERACTIONS

CVC

parity violation

CPT, QED

ATOMIC PHYSICS

MOLECULAR & CLUSTER PHYSICS

laser + microwave spectroscopy

Reactions, life-times

METROLOGY

kilogram

fine structure constant

frequency standards

PLASMA PHYSICS

Ordered structures

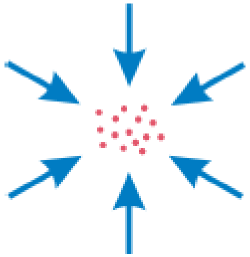
ION BEAM MANIPULATION

cooling *accumulation*

beam-bunching *new accelerator concepts*

ultra-high mass separation

How to trap particles ?



-Required : potential minimum in 3 dimensions

-Desired : harmonic force in direction of the trap center

↳ - ideal oscillator
- constant amplitude
- evolution around a stable equilibrium
- constant frequency during the time

$$\vec{F} = -e.\nabla\Phi \propto -\vec{r} \quad \rightarrow \quad \Phi = Ax^2 + By^2 + Cz^2 \quad A, B, C > 0 \text{ to have a minimum}$$

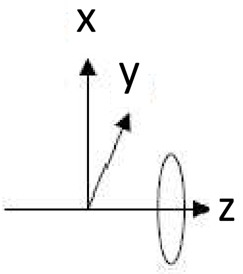
- Laplace's equation : $\Delta\Phi = 0$

$$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} + \frac{\partial^2\Phi}{\partial z^2} = 0 \quad \rightarrow A+B+C=0$$

At least one constant <0

↳ unstable in that coordinate

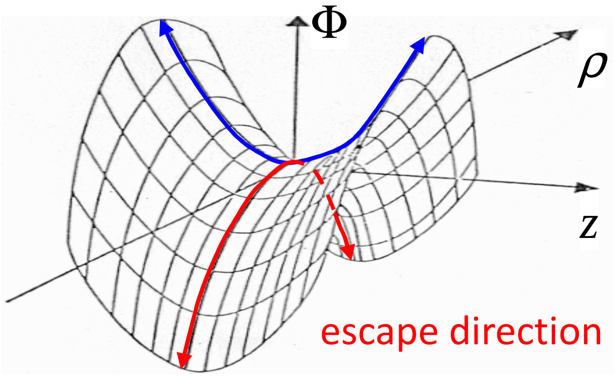
- Simplification : rotational symmetry along the beam axis z



$$\Phi = \frac{U_0}{2d_0^2}(x^2 + y^2 - 2z^2) = \frac{U_0}{2d_0^2}(\rho^2 - 2z^2)$$

saddle point at the origin
- minimum for one coordinate
- maximum for one coordinate

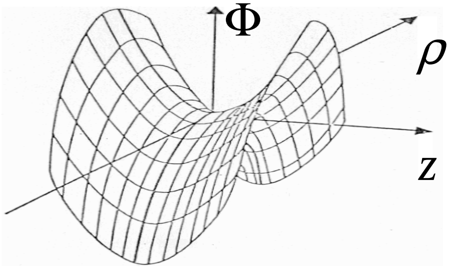
trapping direction



escape direction

How to trap particles ?

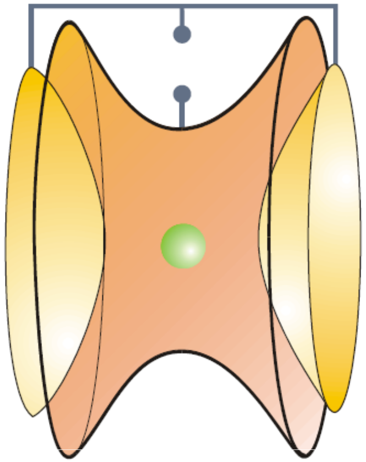
- How to generate such a harmonic potential ?



$$\Phi = \frac{U_0}{2d_0^2}(\rho^2 - 2z^2)$$

- we want equipotential surfaces : $\rho^2 - 2z^2 = cst$ → Hyperboloidal shape

geometry of ring electrode	$\rho^2 - 2z^2 = \rho_0^2$
geometry of endcaps	$\rho^2 - 2z^2 = -2z_0^2$
characteristic trap dimension	$d_0^2 = \rho_0^2 + 2z_0^2$
minimum radius of ring electrode	ρ_0
minimum distance between endcaps	$2z_0$

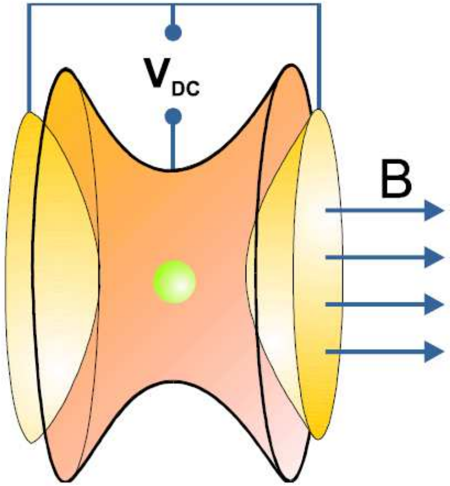


- How to trap particles with such a harmonic potential ?

SOLUTION:

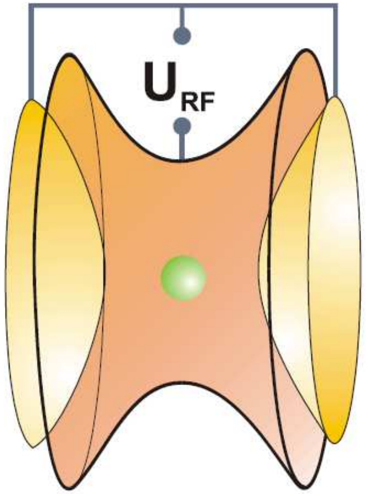
a: superposition of magnetic field in *z*-direction:

Penning trap



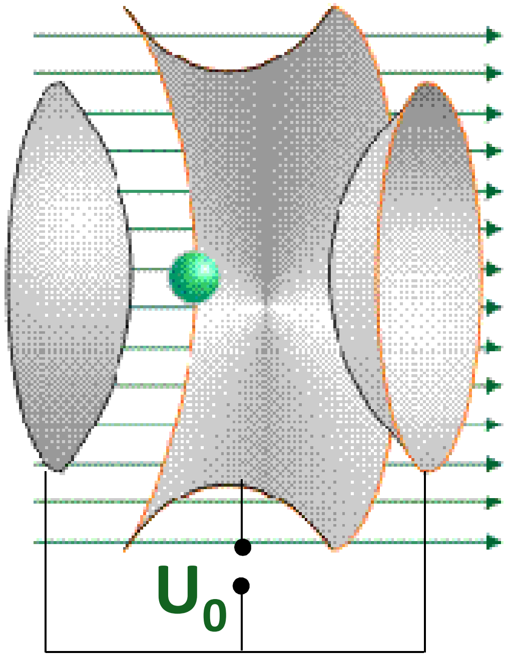
b: time varying voltage (RF) between ring electrode and endcaps:

Paul trap

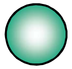


Storage of ions in a Penning trap

$$\Phi = \frac{U_0}{2d_0^2}(x^2 + y^2 - 2z^2) = \frac{U_0}{2d_0^2}(\rho^2 - 2z^2)$$

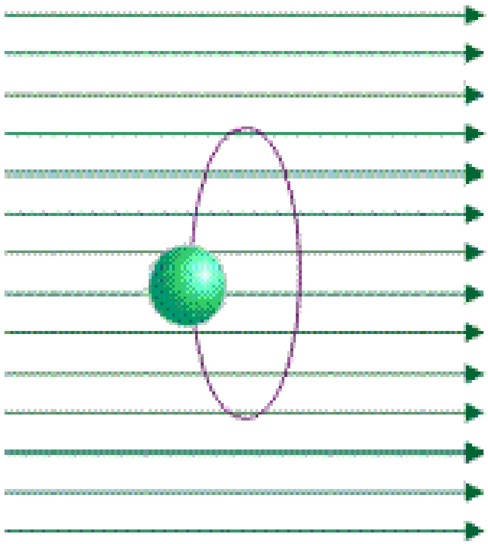


Ion *q/m*



Charge *q*

Mass *m*



Ion the beam axis (ρ=0), the particle oscillates with the axial frequency ω_z :

$$\omega_z = \sqrt{\frac{2qU_0}{md_0^2}}$$

On the plane z=0, the particle moves on a circular orbit with the cyclotron frequency ω_c :

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

Storage of ions in a Penning trap

Force : quadrupolar potential + Lorentz : $\vec{F} = q\vec{E}(r) + q\vec{v} \otimes \vec{B}$

Equation of motion : $\vec{F} = -q\vec{\nabla}\Phi(r) + q\vec{v} \otimes \vec{B} = m\ddot{\vec{r}}$ $\Phi = \frac{U_0}{2d_0^2}(\rho^2 - 2z^2)$

Axial direction : B=Bz

→ force is purely electrostatic

→ $\ddot{z} = -\omega_z^2 z$ → harmonic oscillation in z $\omega_z = \sqrt{\frac{2qU_0}{md_0^2}}$

with $qU_0>0$

Radial direction : the x and y component of the force are combination of

- a dominant restraining force due to B (characterized by ω_c)
- a repulsive electrostatic force that tries to push the particles out of the trap

→ coupled radial equations

$$\rightarrow \left| \begin{array}{l} \ddot{x} = \frac{\omega_z^2}{2} x - \omega_c y \\ \ddot{y} = \frac{\omega_z^2}{2} y + \omega_c x \end{array} \right.$$

substitution

$u = x + iy$

$\omega_c = \frac{q}{m} B$ $i\omega_c \dot{u} - \frac{\omega_z^2}{2} u + \dot{u} = 0$

$u(t) = u_0 e^{-i\omega t}$

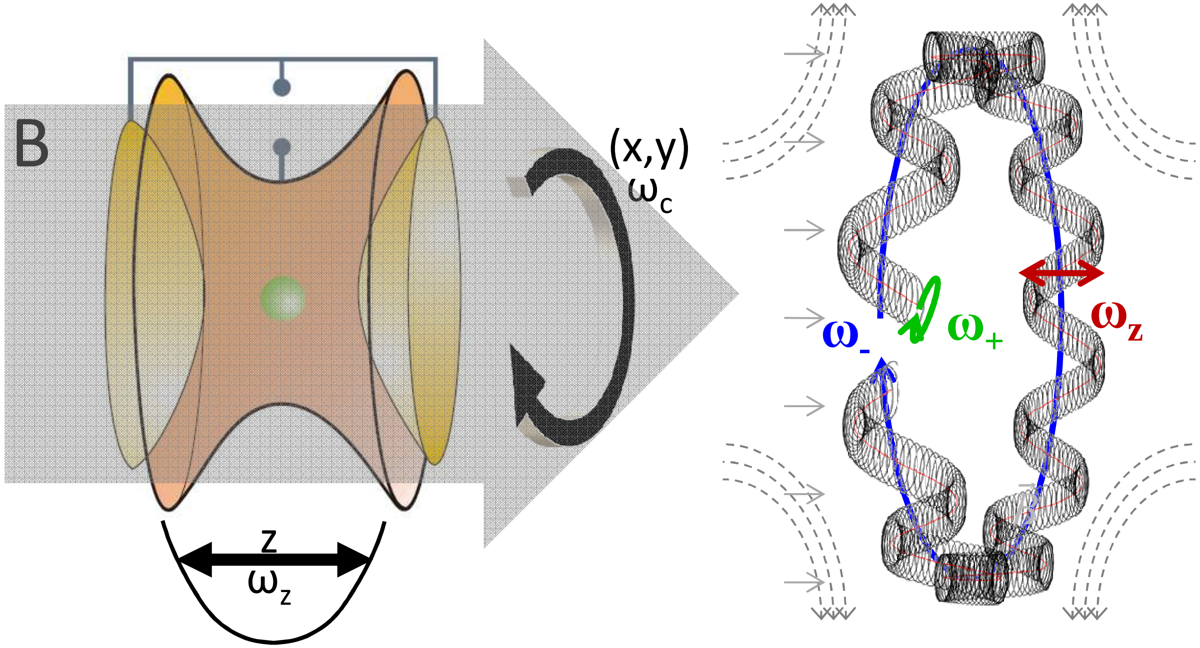
modified (by E)
cyclotron frequency

$$\omega_+ = \frac{\omega_c}{2} + \frac{\omega_c}{2}\sqrt{1 - \frac{2\omega_z^2}{\omega_c^2}}$$

magnetron
frequency

$$\omega_- = \frac{\omega_c}{2} - \frac{\omega_c}{2}\sqrt{1 - \frac{2\omega_z^2}{\omega_c^2}}$$

Movement of ions in a Penning trap



axial motion

$$\omega_z = \sqrt{\frac{qU_{dc}}{md^2}}$$

ω_z ~ 100 kHz

$E_p \Leftrightarrow E_k$

magnetron motion

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

ω_- ~ kHz

~E_p

modified cyclotron motion

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

ω_+ ~ 10MHz

~E_K

3 independent motions at 3 eigenfrequencies

The free cyclotron frequency is inverse proportional to the mass of the ions!

$$\omega_c = qB/m$$

$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$

$\omega_c = \omega_+ + \omega_-$

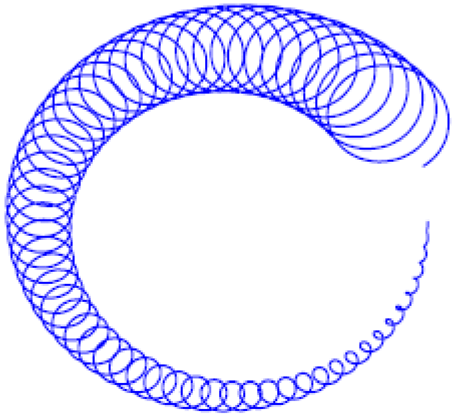
→Possibility to "manipulate" the ions
- by increasing one of the motions (excitations)
- by reducing one of the motions (cooling)
- by transferring one motion to another one

Manipulation of ions in a Penning trap

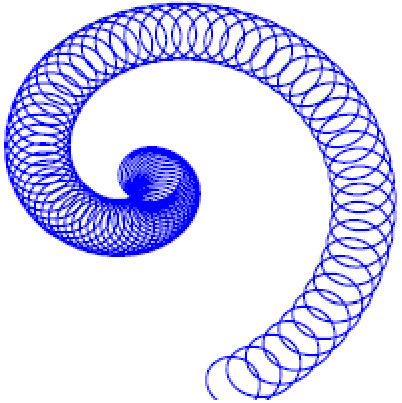
1- Dipolar azimuthal excitation :

either of the ion's radial motions can be excited by
an electric dipole field in resonance with the motion frequency
→ amplitude of the motion increases/decreases

Cyclotron excitation:

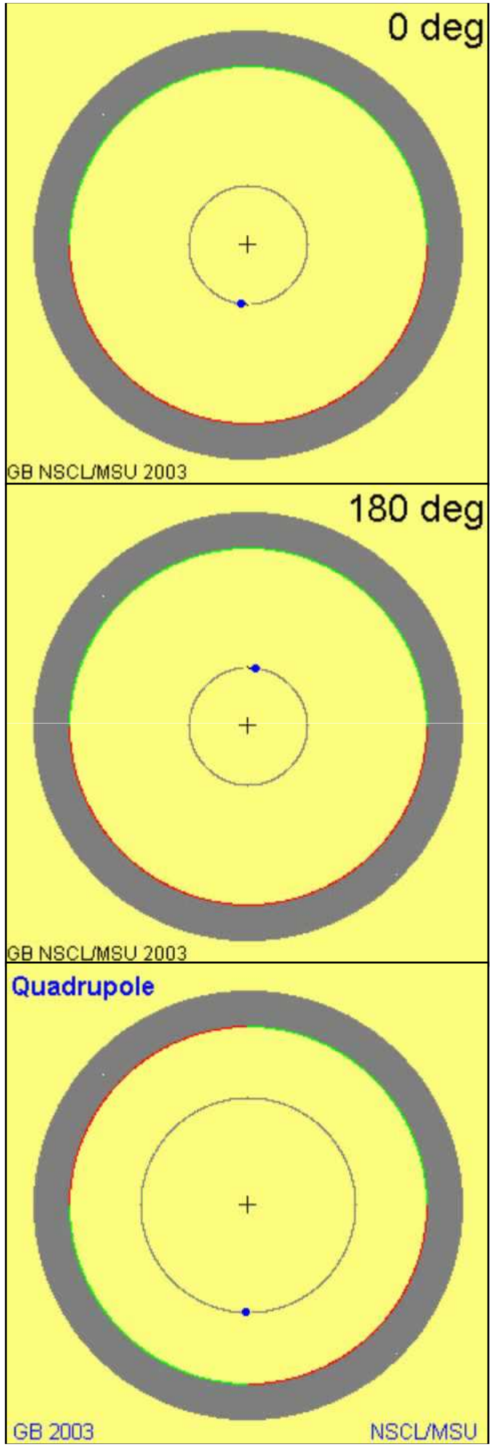


Magnetron excitation:



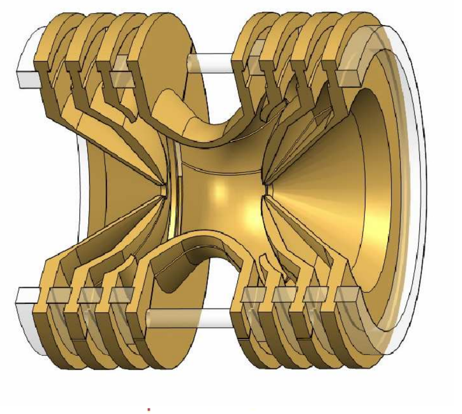
2- Quadrupolar azimuthal excitation :

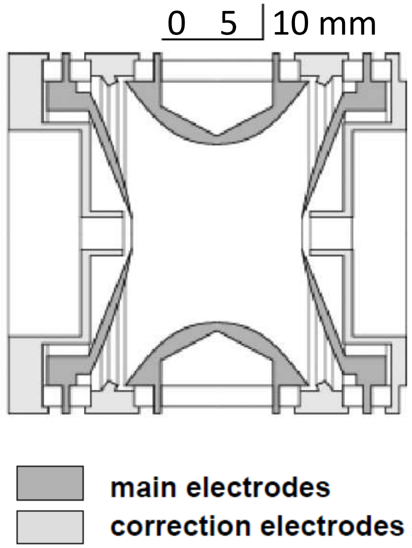
if the two radial motions are excited at their
sum frequency, they are coupled
→ continuously converted into each other



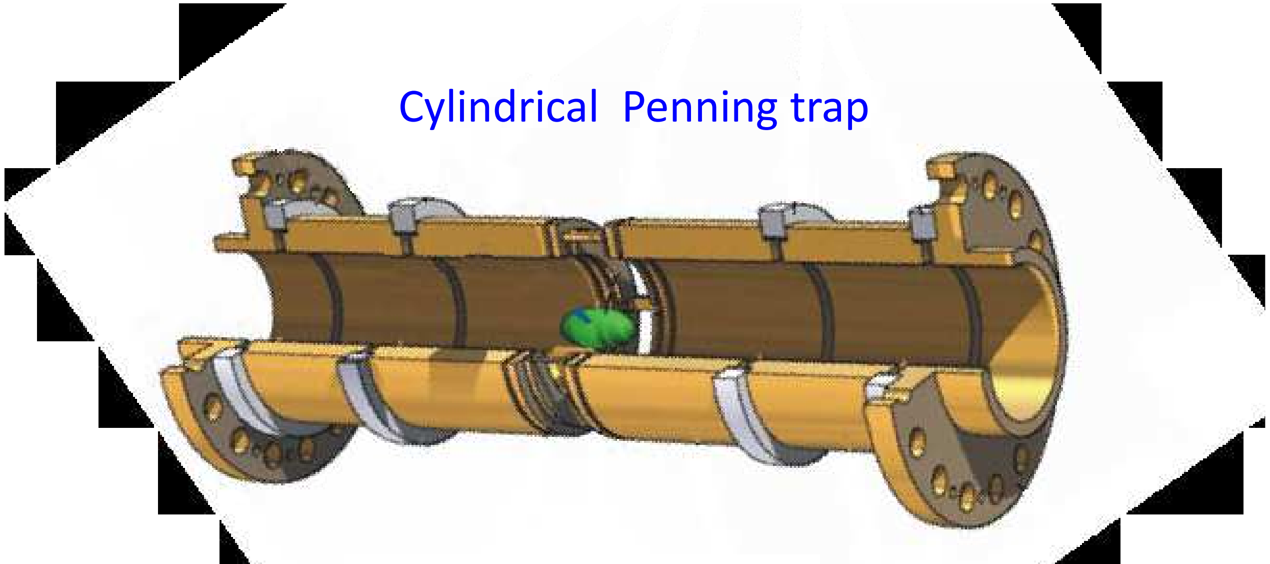
Penning trap geometries

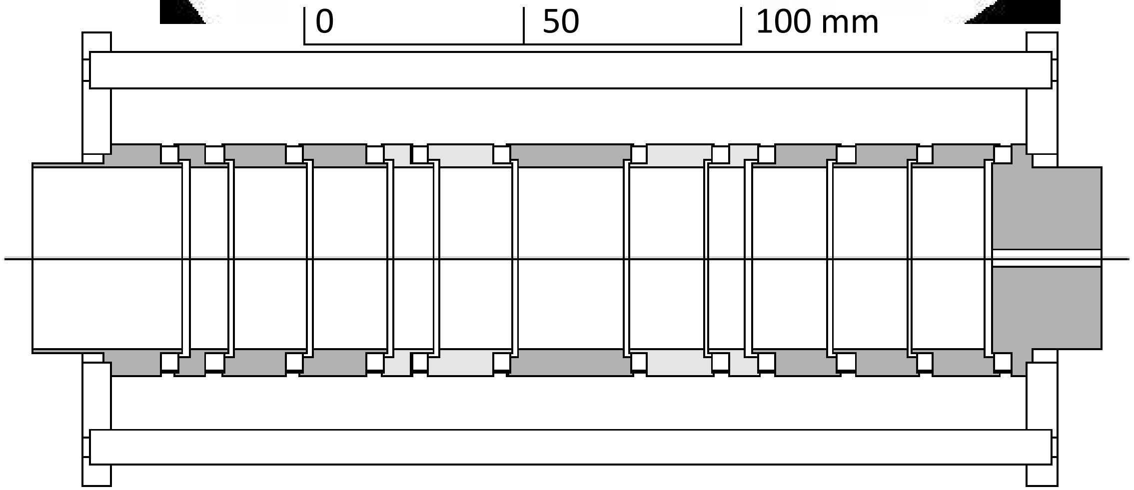
Hyperbolical Penning trap

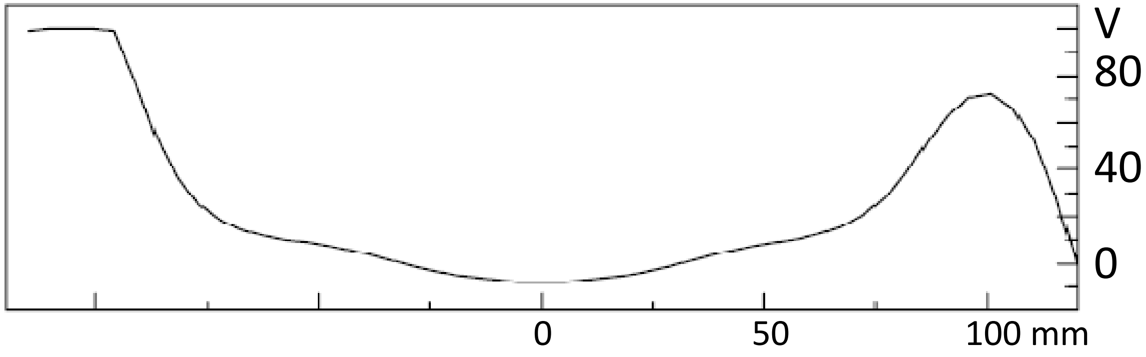




Cylindrical Penning trap

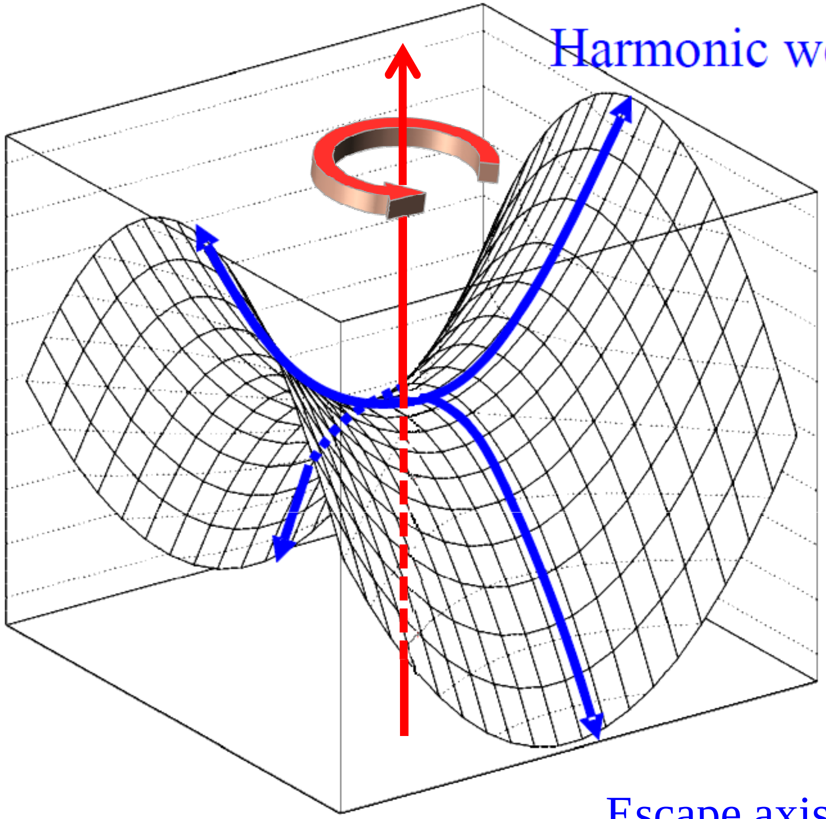






Storage of ions in a Paul trap

Rotating E field



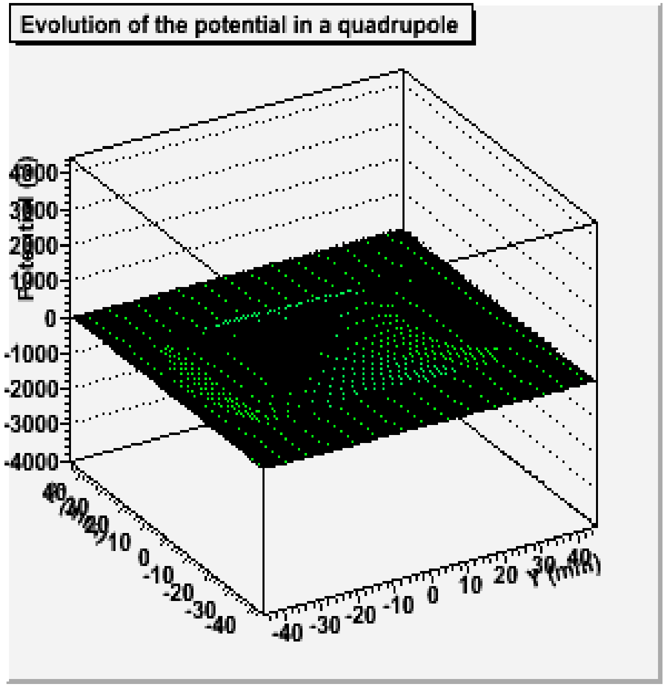
Harmonic well

Escape axis

PAUL TRAP

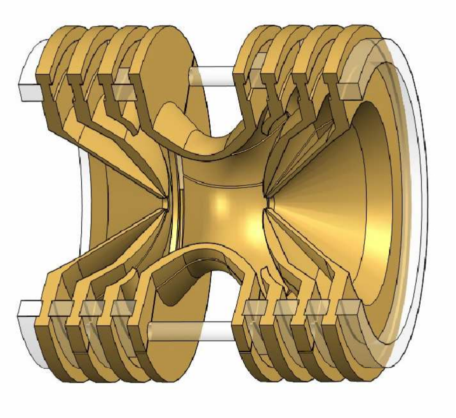
$$\Phi = \frac{U_0}{2d_0^2}(x^2+y^2-2z^2) = \frac{U_0}{2d_0^2}(\rho^2-2z^2)$$

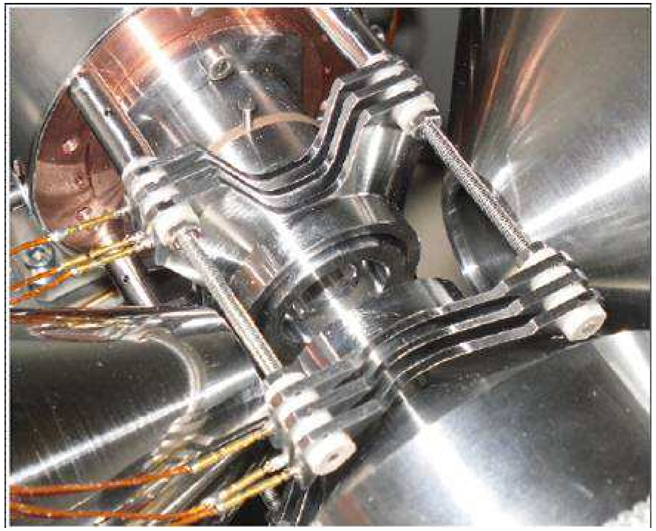
$$U_0 \rightarrow U_0+V_0\cos\Omega t$$



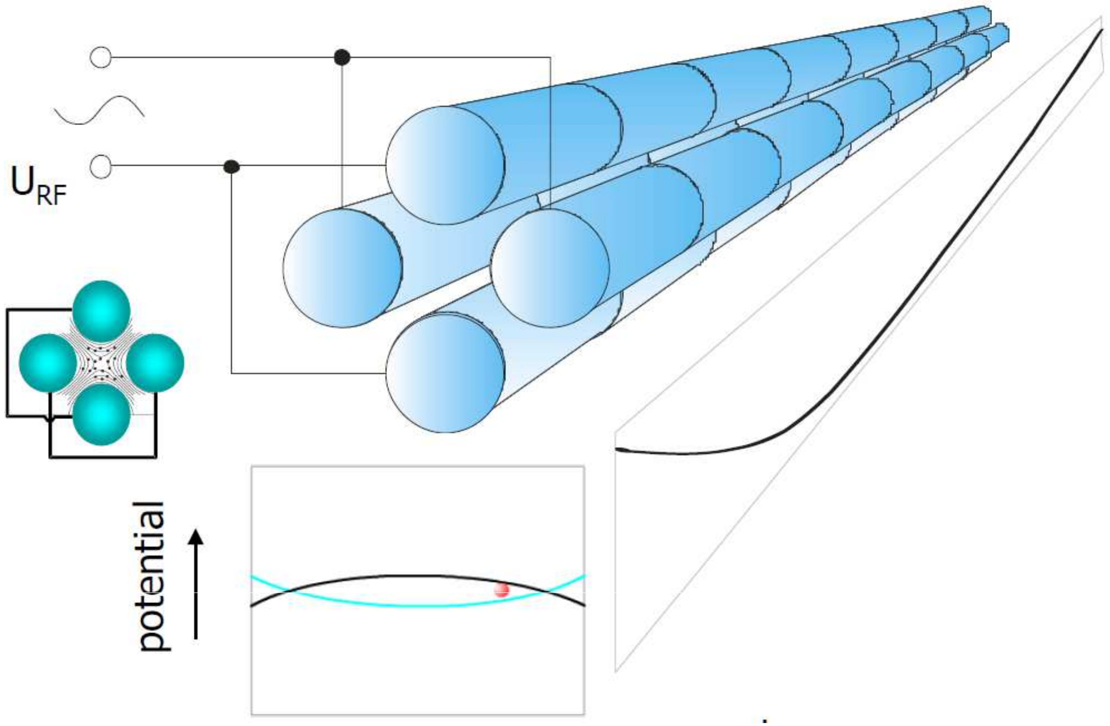
Paul trap geometries

Hyperbolical Paul trap





Linear Paul trap



Storage of ions in a Paul trap

Force : radiofrequency quadrupolar potential $\vec{F} = q\vec{E}(r)$

Equation of motion : $-q\vec{\nabla}\Phi(r,t) = m\ddot{\vec{r}}$

$$\Phi = \frac{U_0 + V_0\cos\Omega t}{2d_0^2}(\rho^2 - 2z^2)$$

$$\left|\begin{array}{l} \dfrac{q(U_0+V_0\cos\Omega t)}{m\rho_0^2}\rho + \ddot{\rho} = 0 \\ -\dfrac{q(U_0+V_0\cos\Omega t)}{m\rho_0^2}z + \ddot{z} = 0 \end{array}\right.$$

⇨

substitution

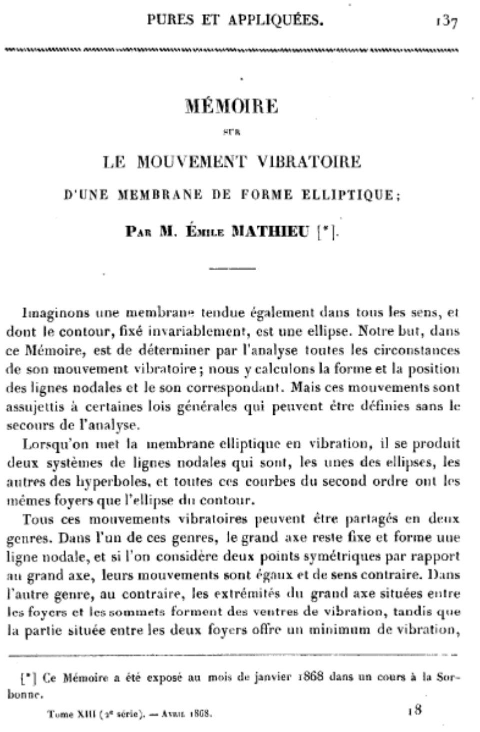
$\tau = \frac{\Omega}{2}t$ $\quad a_z = -2a_r = -\frac{8qU_0}{mr_0^2\Omega^2}$

$u = x, y, z$ $\quad q_z = -2q_r = \frac{4qV_0}{mr_0^2\Omega^2}$

⇨

$$\boxed{\frac{d^2u}{d\tau^2} + (a_u - 2q_u\cos 2\tau)u = 0}$$

Mathieu differential equation



PURES ET APPLIQUÉES. 137

MÉMOIRE

SUR

LE MOUVEMENT VIBRATOIRE

D'UNE MEMBRANE DE FORME ELLIPTIQUE;

Par M. Émile MATHIEU [*].

Imaginons une membrane tendue également dans tous les sens, et dont le contour, fixé invariablement, est une ellipse. Notre but, dans ce Mémoire, est de déterminer par l'analyse toutes les circonstances de son mouvement vibratoire; nous y calculons la forme et la position des lignes nodales et le son correspondant. Mais ces mouvements sont assujettis à certaines lois générales qui peuvent être définies sans le secours de l'analyse.

Lorsqu'on met la membrane elliptique en vibration, il se produit deux systèmes de lignes nodales qui sont, les unes des ellipses, les autres des hyperboles, et toutes ces courbes du second ordre ont les mêmes foyers que l'ellipse du contour.

Tous ces mouvements vibratoires peuvent être partagés en deux genres. Dans l'un de ces genres, le grand axe reste fixe et forme une ligne nodale, et si l'on considère deux points symétriques par rapport au grand axe, leurs mouvements sont égaux et de sens contraire. Dans l'autre genre, au contraire, les extrémités du grand axe situées entre les foyers et les sommets forment des ventres de vibration, tandis que la partie située entre les deux foyers offre un minimum de vibration,

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[*] Ce Mémoire a été exposé au mois de janvier 1868 dans un cours à la Sorbonne.

Tome XIII (2e série). — Avril 1868. 18

E Mathieu, J Appl Math, 1868

$$\boxed{u(t) = A\sum_{n=-\infty}^{\infty} C_{2n}\cos(\beta + 2n)\Omega t/2 + B\sum_{n=-\infty}^{\infty} C_{2n}\sin(\beta + 2n)\Omega t/2}$$

exact solution

- A, B: constants → depend on the initial conditions
- C_{2n}: Amplitudes of the Fourier components of the particle motion
- $\omega_u = \beta_u \Omega$

micro motion (fast)

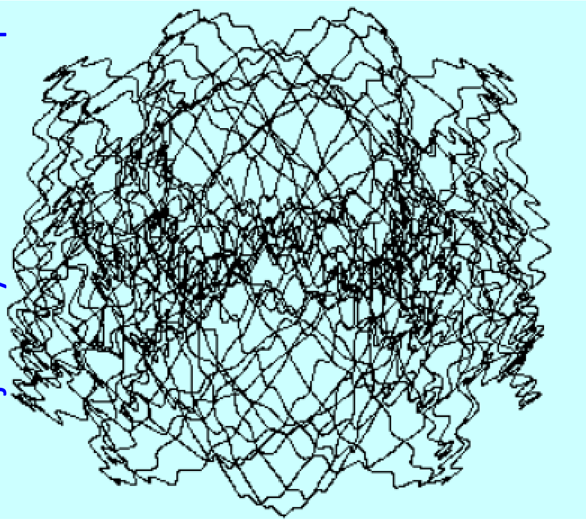
macro motion (slow)

$$\beta_u^2 = a_u + \cfrac{q_u^2}{(\beta_u+2)^2 - a_u - \cfrac{q_u^2}{(\beta_u+4)^4 - a_u - \cfrac{q_u^2}{(\beta_u+6)^2 - a_u - \cdots}}} + \cfrac{q_u^2}{(\beta_u-2)^2 - a_u - \cfrac{q_u^2}{(\beta_u-4)^2 - a_u - \cfrac{q_u^2}{(\beta_u-6)^2 - a_u - \cdots}}}$$

Ion trajectory in a Paul trap and Stability

$$u(t) \propto \left[1-\frac{q_u}{2}\cos\Omega t\right]\cos(\omega_u t-\rho)=0$$

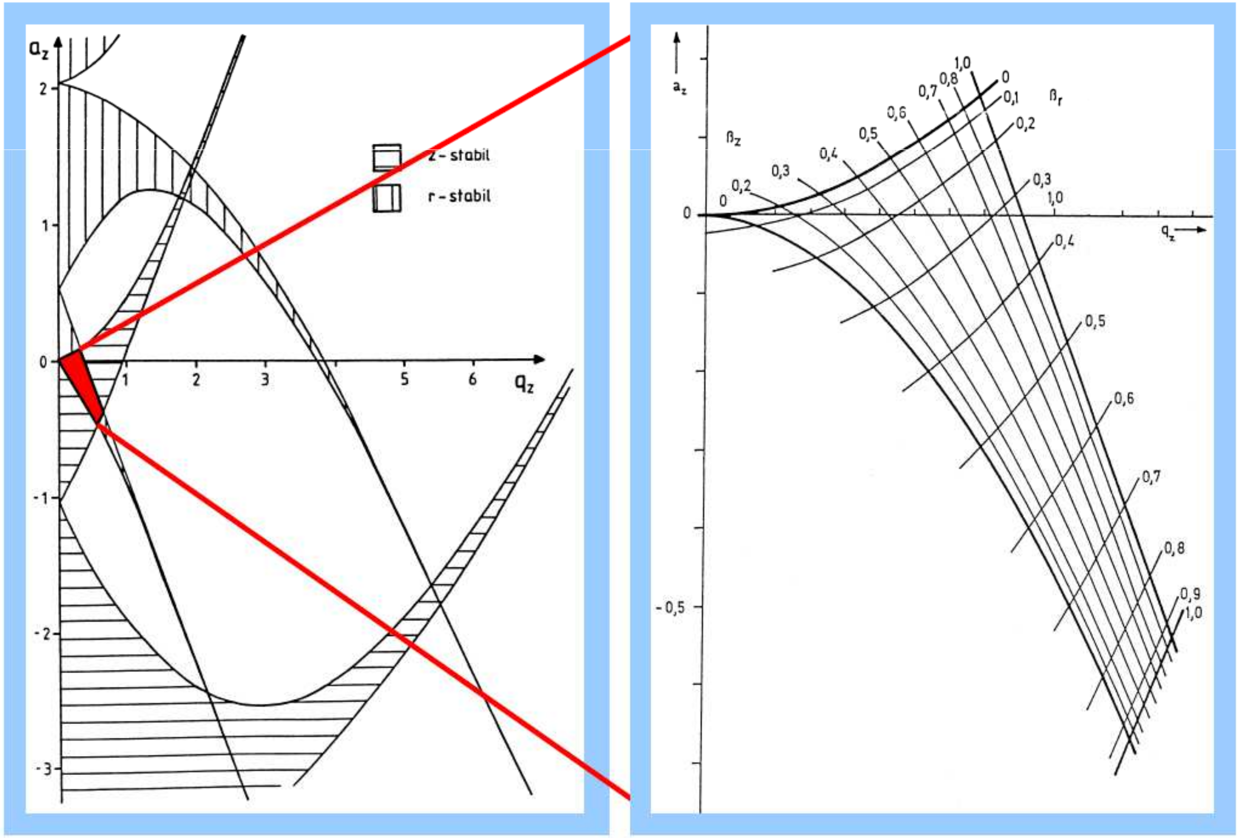
ω_u: macro motion (slow)
Ω: micro motion (fast, RF)



Ion trajectory – 3D Paul Trap

-Stability depends on q and a values

→ depends on : q/m, r_0, Ω, U_0 and V_0
→ Stability diagram



$$a_z = -2a_r = -\frac{8qU_0}{mr_0^2\Omega^2}$$

$$q_z = -2q_r = \frac{4qV_0}{mr_0^2\Omega^2}$$

m/q : given by the physics
r_0 : dimension of the trap
U_0, V_0 : applied voltages
Ω : applied frequency

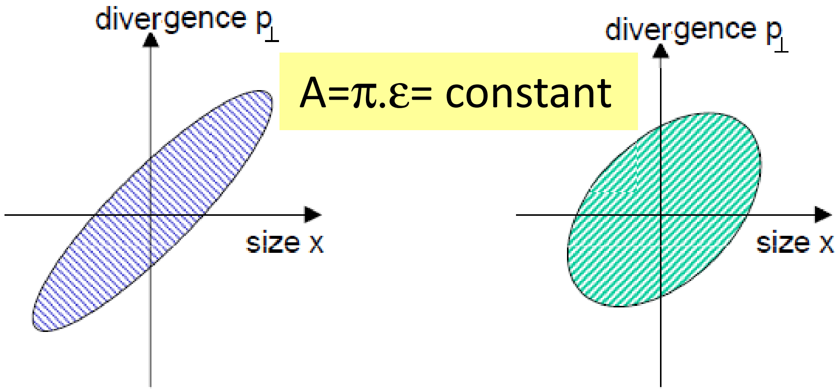
you are able to choose r_0, U_0, V_O and Ω to have a stable solution for a given m/q

What is cooling ?

Cooling = enhancement of the phase space density of a beam

i.e. simultaneous reduction of size and angular divergence
(transverse momentum)

i.e. reduction of its emittance



A=π.ε= constant

But : Liouville's theorem :

"For a given energy (velocity), the emittance e (mm.mrad) -the product of size and angular divergence- must be constant if there are only conservative forces"

Solution : cooling possible if external interaction is applied

for ions :	→ with electrons	electron cooling
	→ with atoms	buffer gas cooling
	→ with lasers	laser cooling
	…	

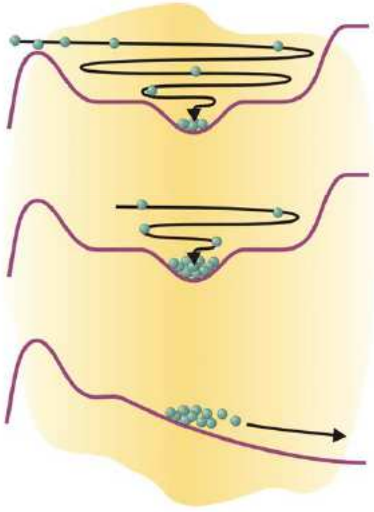
Why Cooling ?

Cooling is important for :

- the beam preparation (e.g. by use of RFQ -RadioFrequency Quadrupole- Paul trap)

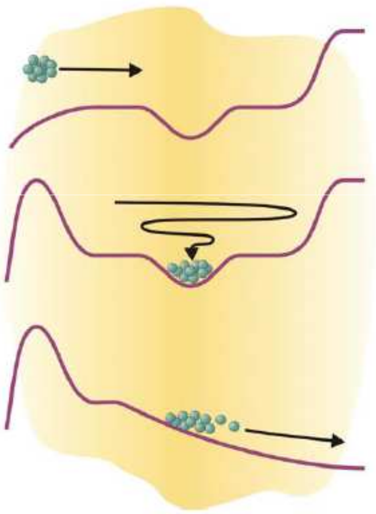
→ to bunch the beam (ovoid losses)

continuous injection



→to inject properly the ions in a trap (small trapping potentials)

pulsed injection

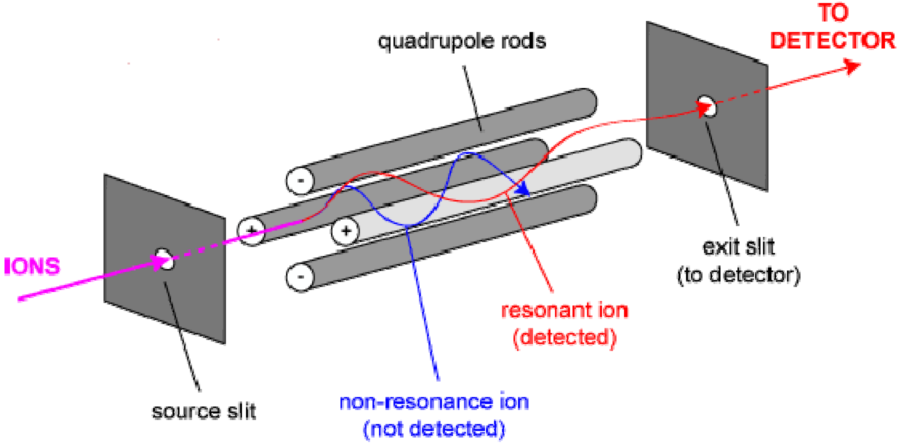


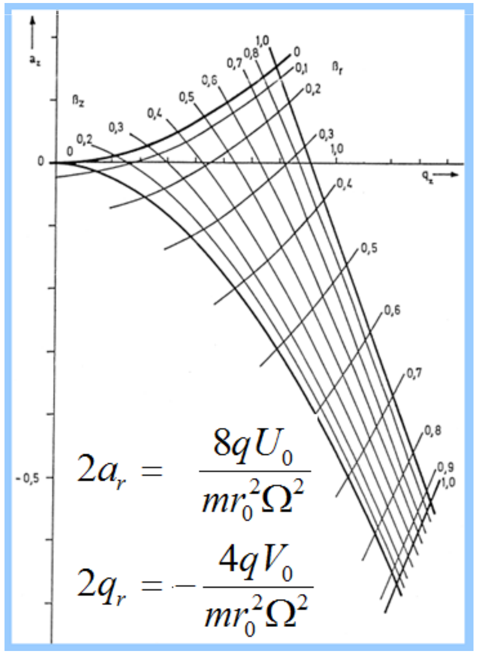
- the manipulation of the ions in the trap (e.g. mass selective centering in Penning tarp)

Increase : - accuracy
- sensitivity
- efficiency

Quadrupole Mass Analyzer

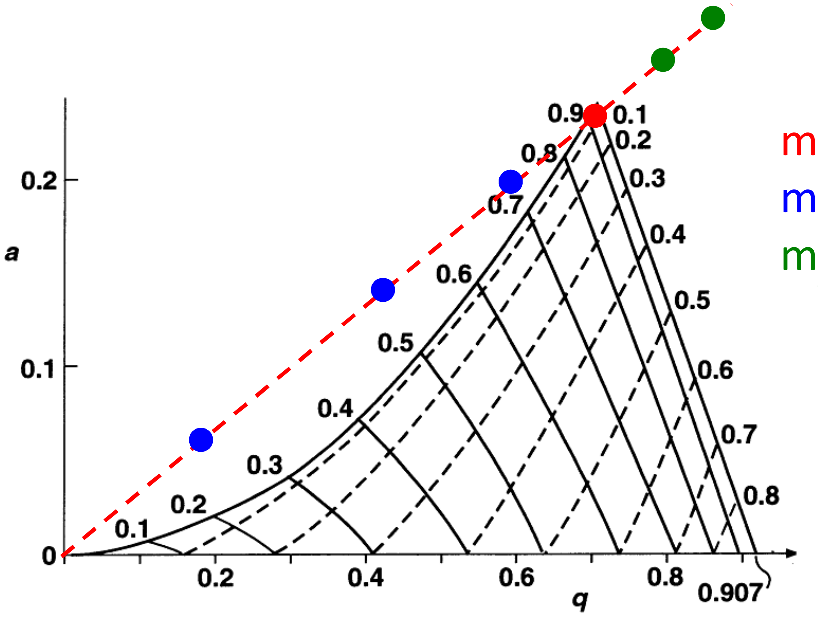
linear Paul "trap" (no z trapping)





$$2a_r = \frac{8qU_0}{mr_0^2\Omega^2}$$

$$2q_r = -\frac{4qV_0}{mr_0^2\Omega^2}$$

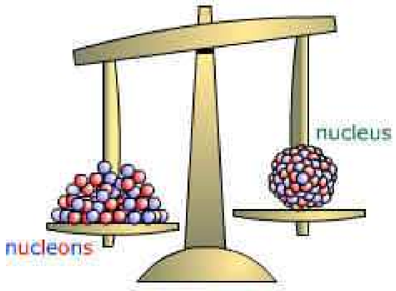


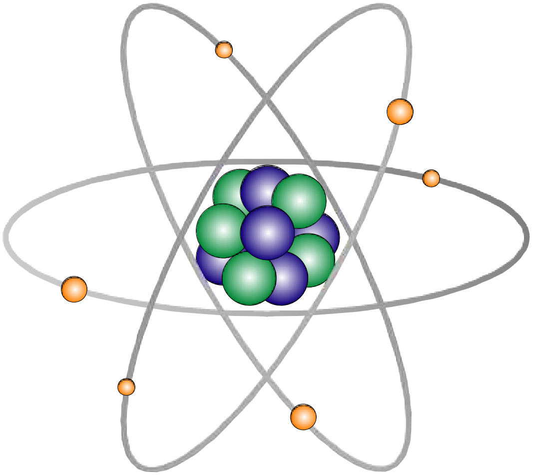
m_0 → U_0, V_0 and Ω

$m_i > m_0$

$m_j < m_0$

Why to measure (precisely) masses ?





$= N \cdot$ 🟢 $+ Z \cdot$ 🔵 $+ Z \cdot$ 🟠

– binding energy

Nuclear physics is here…
n-n(-n) interaction

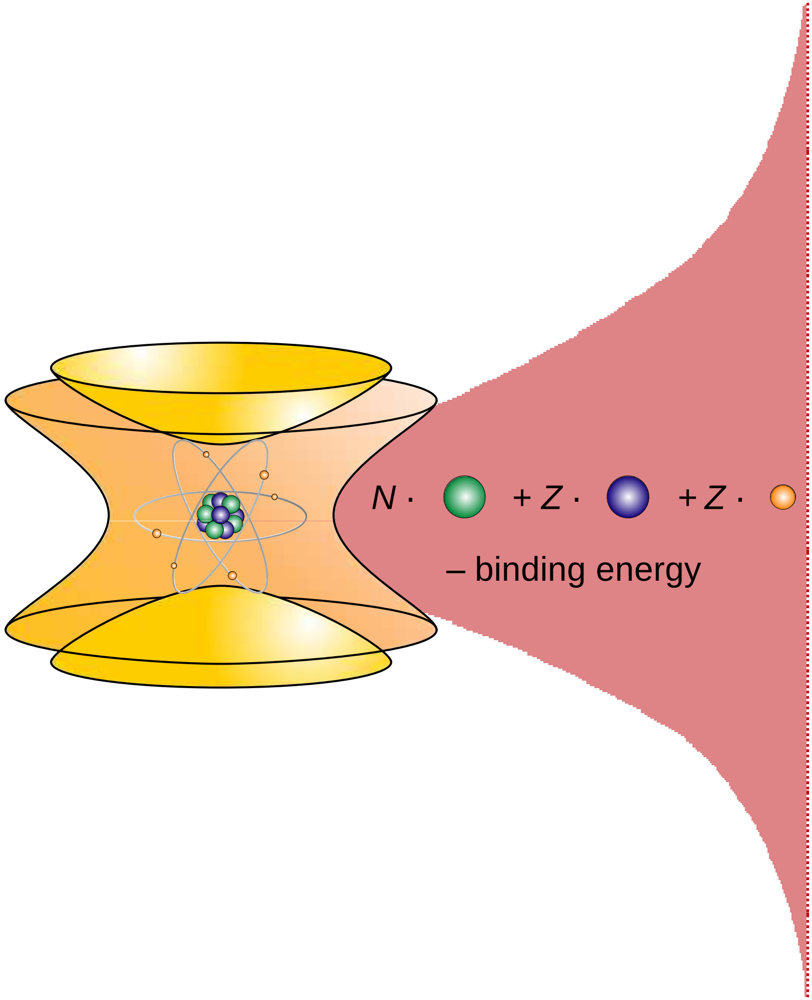
$$M_{Atom} = N\bullet m_{neutron} + Z\bullet m_{proton} + Z\bullet m_{electron} - (B_{atom} + B_{nucleus})/c^2$$

$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} – 10^{-8}$

Masses determine the atomic and nuclear binding energies
→ reflect all forces in the atom/nucleus.

Why to measure (precisely) masses ?

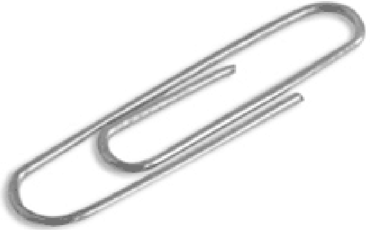


	δm/m
General physics & chemistry	≤ 10^{-5}
Nuclear structure physics - separation of isobars	≤ 10^{-6}
Astrophysics - separation of isomers	≤ 10^{-7}
Weak interaction studies	≤ 10^{-8}
Metrology - fundamental constants Neutrino physics	≤ 10^{-9}
CPT tests	≤ 10^{-10}
QED in highly-charged ions - separation of atomic states	≤ 10^{-11}

Why to measure (precisely) masses ?

What does a relative uncertainty of 10^{-8} mean?

weight (empty): 164000 kg

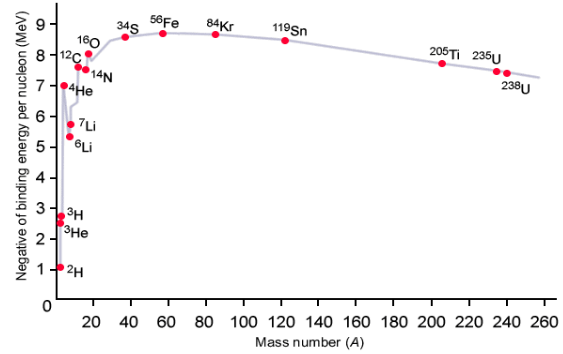


Or one (little) step walking around the Earth!

Why to measure (precisely) masses ?

Nuclear physics is here…
n-n(-n) interaction

$$M_{Atom} = N\bullet m_{neutron} + Z\bullet m_{proton} + Z\bullet m_{electron} - (B_{atom} + B_{nucleus})/c^2$$

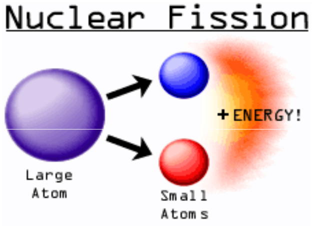


Liquid Drop Model

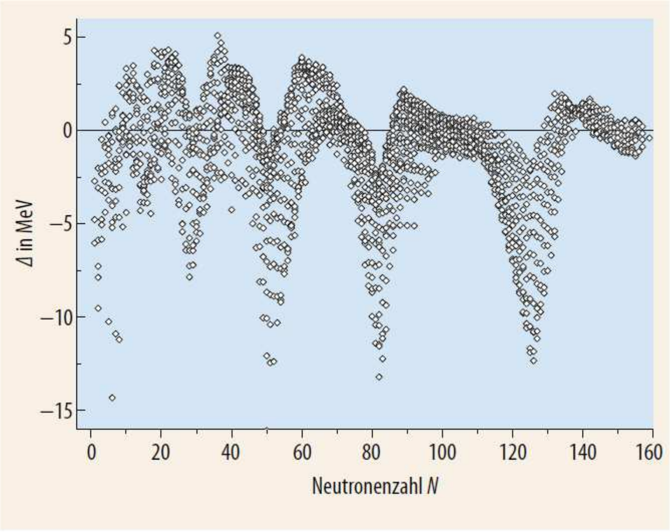
$$B = a_v.A \; -a_s.A^{2/3} \; -a_c.Z(Z-1)/A^{1/3} \; -a_{sym}(Z-N)^2 \; +\Delta$$

Weizsäcker, Zeitschrift der Physik, 96, 431 (1935)

Used in 1935 by Meitner and Frisch to explain the Fission in term of competition between Coulomb and Surface



Comparison B_{nucl}: Theory-experiment



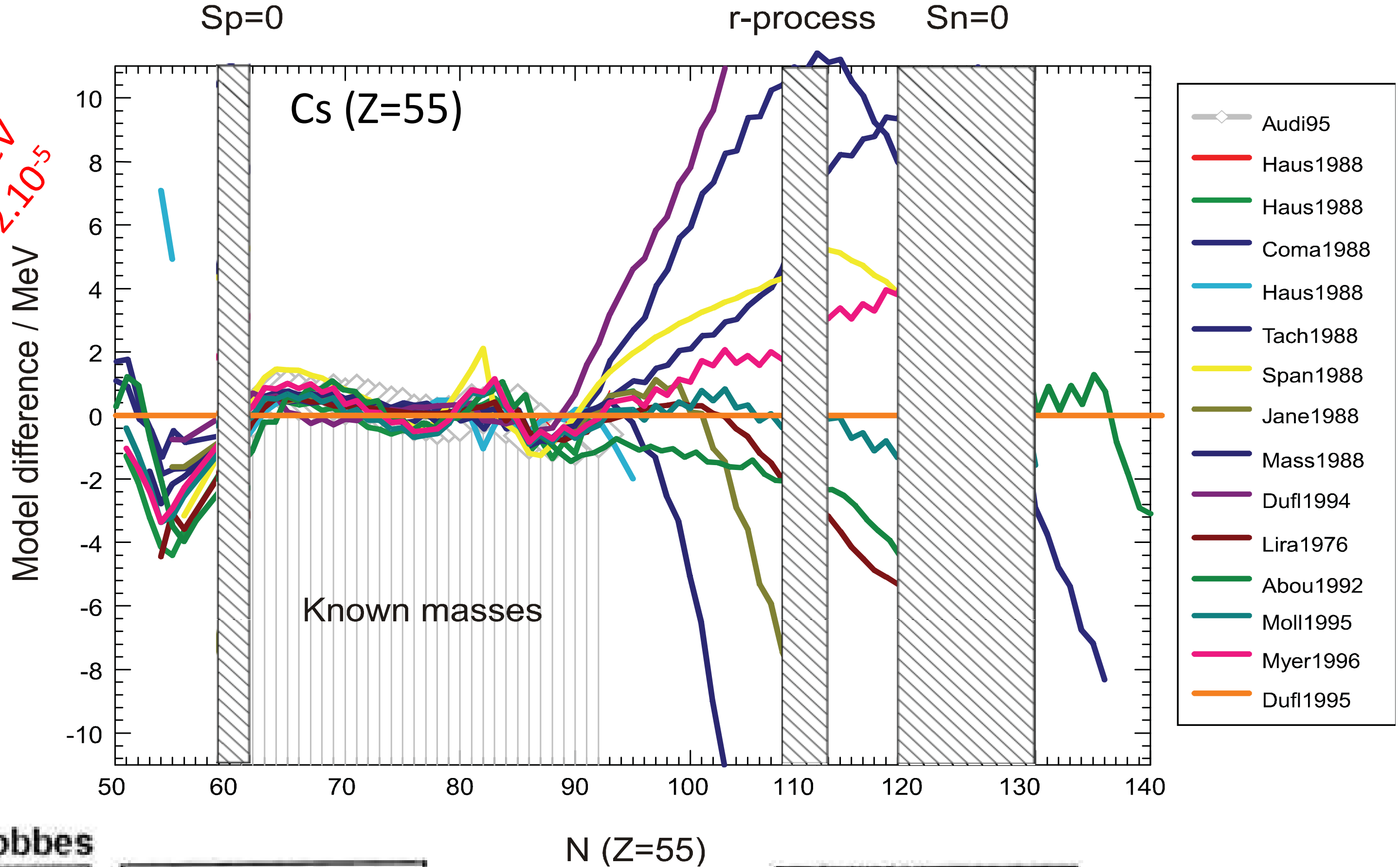
10 MeV difference for masses of 10-100 GeV
→ 10^{-2} to 10^{-3}

→Nuclear structure effects like
shell closures become visible.

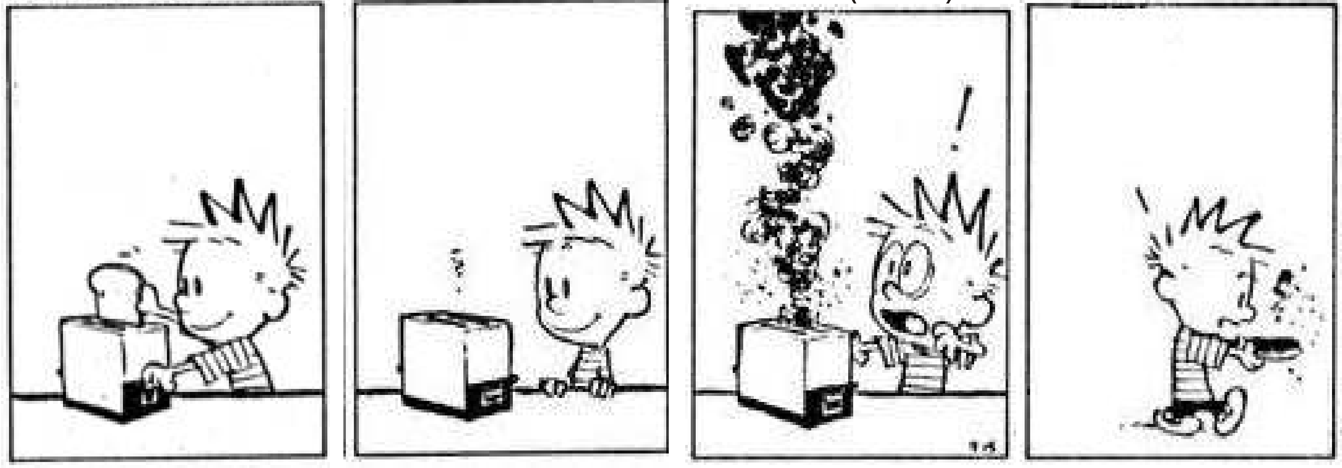
→1949: The shell model and
magic numbers
(Göppert-Mayer + Jensen).

Why to measure (precisely) masses ?

1 MeV over 55 GeV → 2.10^{-5}

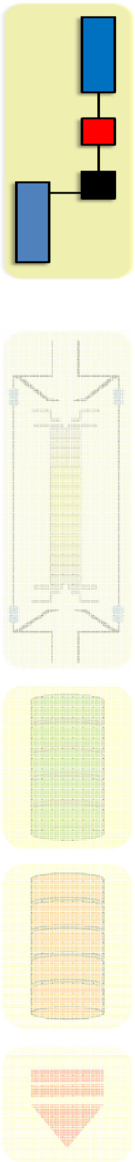


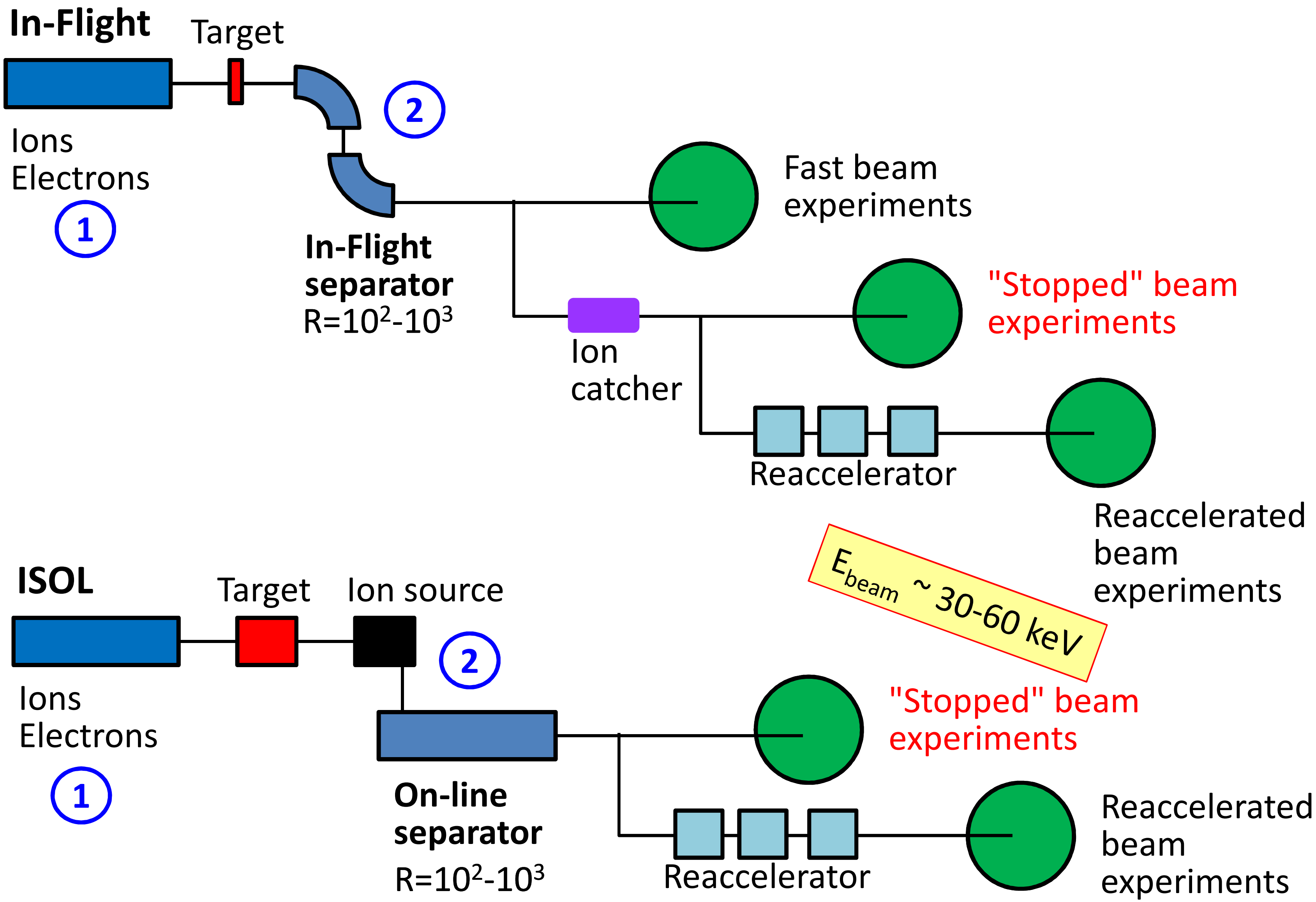
Calvin and Hobbes



How to measure (precisely) masses ?

1 and 2) production of the ions of interest and first selection





In-Flight

Target

Ions
Electrons

①

②

In-Flight separator
R=10^2-10^3

Fast beam experiments

"Stopped" beam experiments

Ion catcher

Reaccelerator

Reaccelerated beam experiments

E_{beam} ~ 30-60 keV

ISOL

Target

Ion source

Ions
Electrons

①

②

On-line separator
R=10^2-10^3

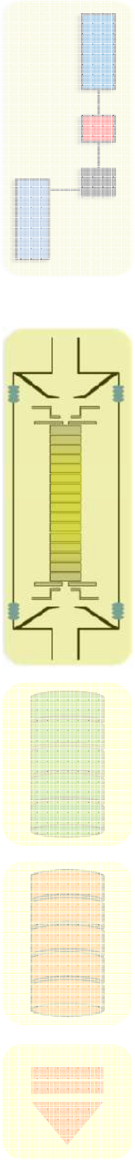
"Stopped" beam experiments

Reaccelerator

Reaccelerated beam experiments

How to measure (precisely) masses ?

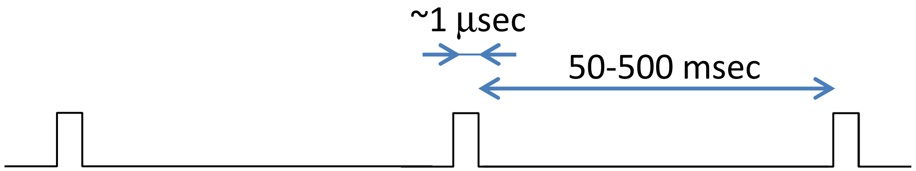
3- beam preparation



In the Penning trap :

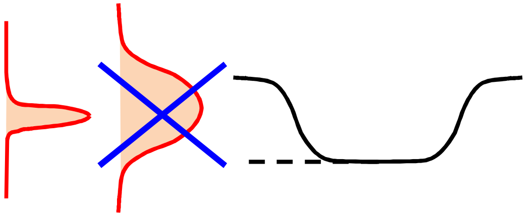
- timing cycles : [50 – 500]msec

  → bunches

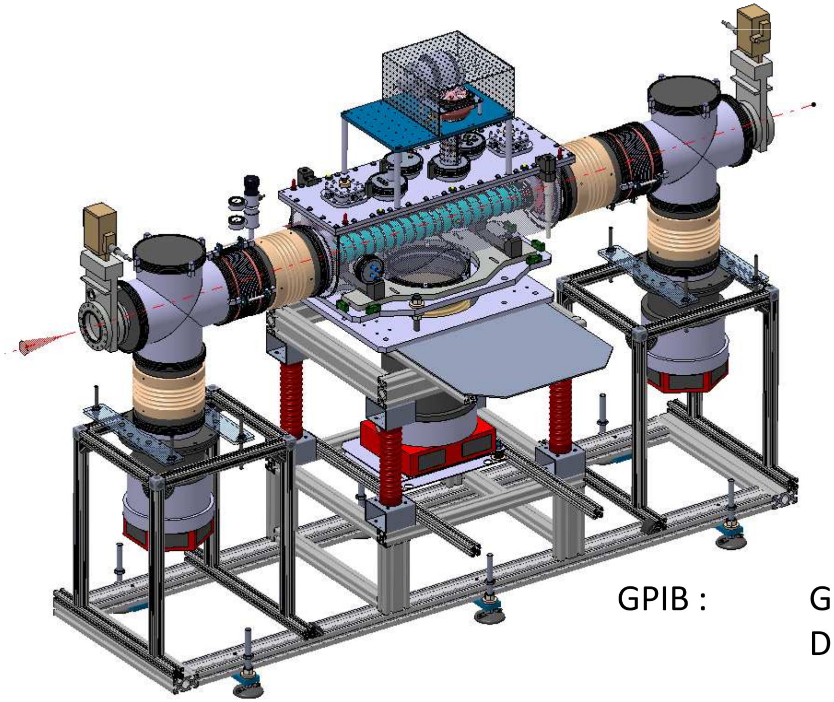


- low trapping voltages : few Volts

  → small energy dispersion i.e. small emittance



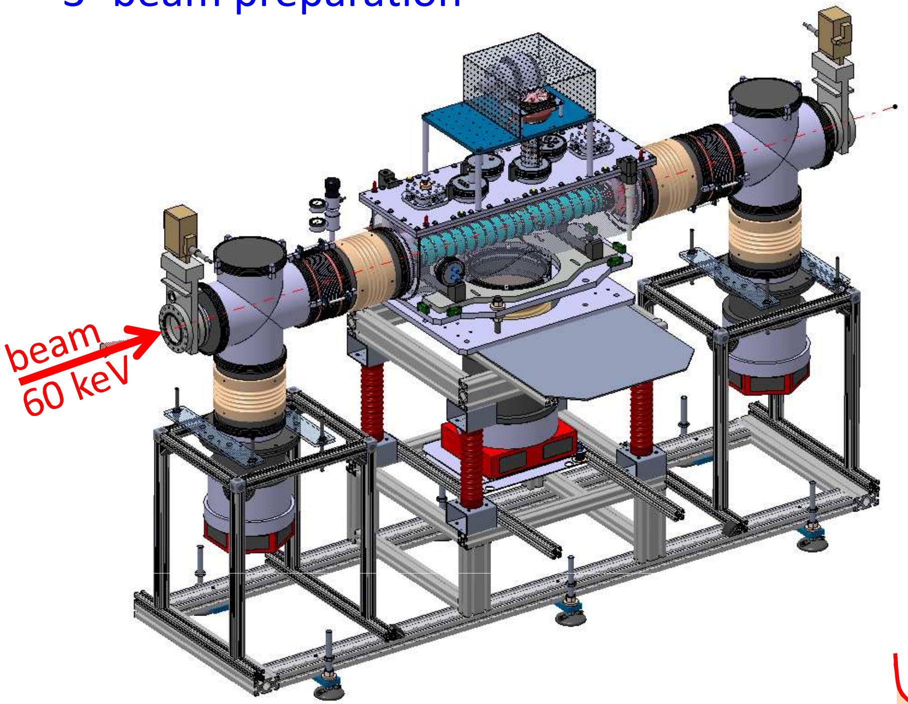
→ radiofrequency quadrupole RFQ (Paul trap)

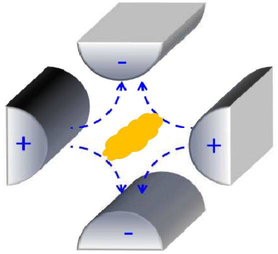


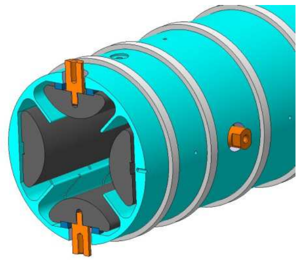
GPIB : General Purpose Ion Buncher
DESIR@SPIRAL2

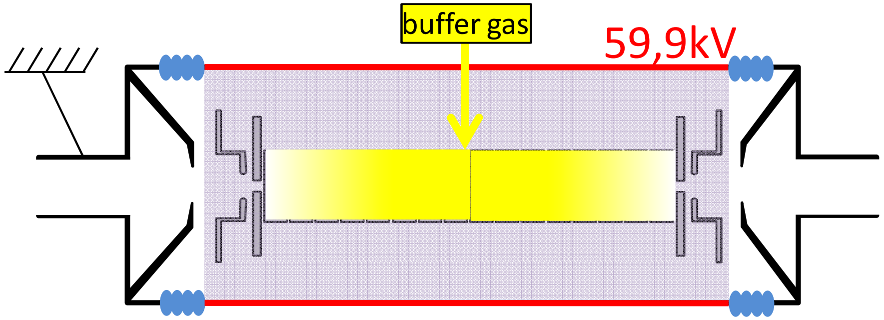
How to measure (precisely) masses ?

3- beam preparation









1 - ions → E_k=60keV; ΔE_k=100eV

2 - potential barrier → E_k~100eV

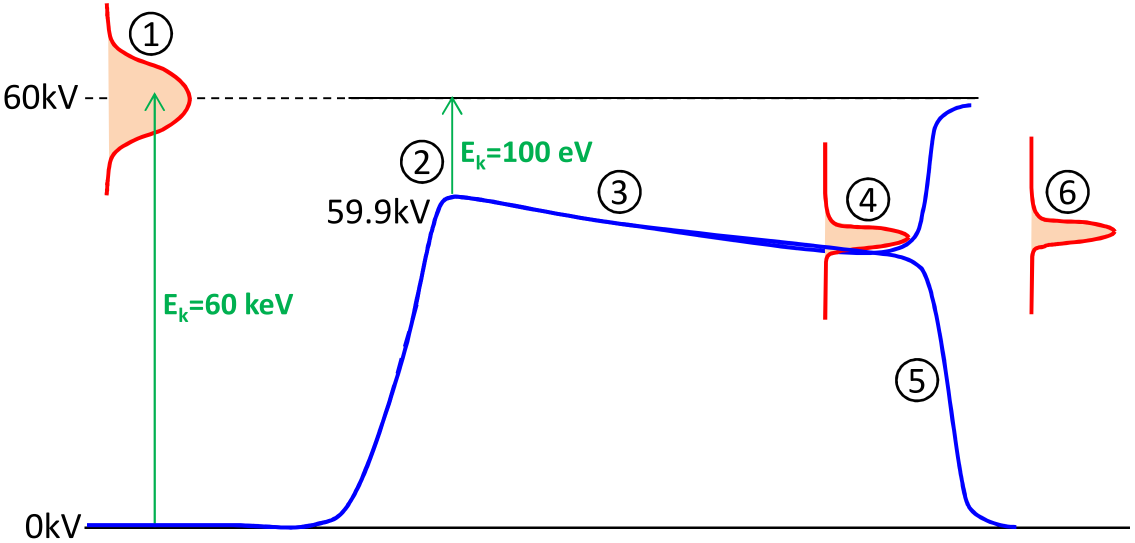
3 - elastic scattering → thermalisation

- RF potential → radial confinement

4 - DC potential → axial confinement

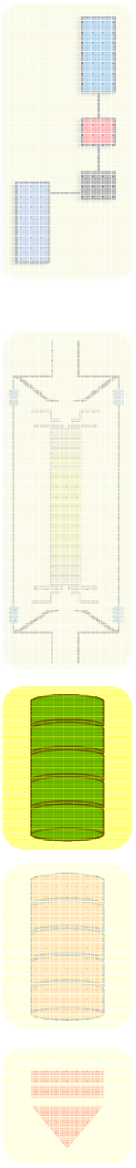
5 - DC potential → bunching

6 - "cooled" ions → E_k=59.9keV; ΔE_k=1eV



How to measure (precisely) masses ?

4- mass measurement → preparation Penning trap

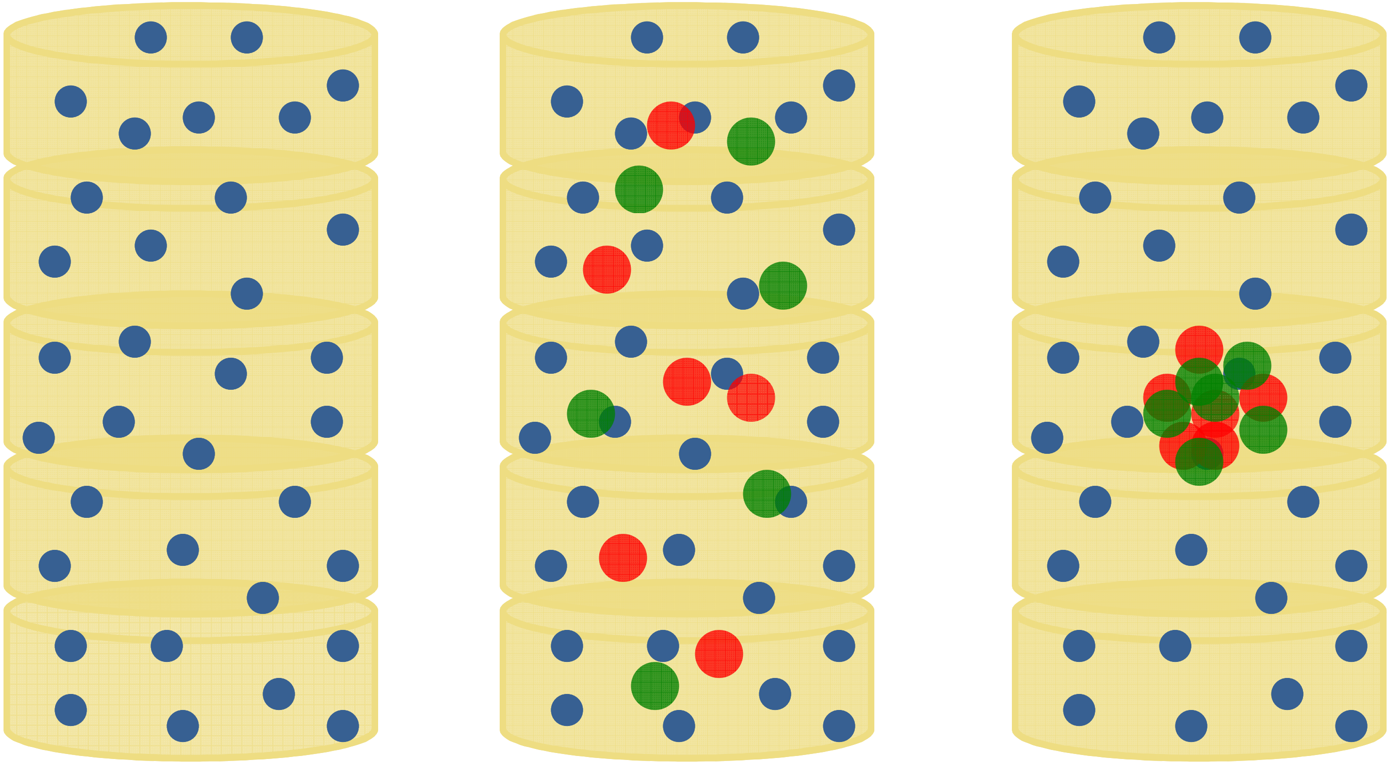


- Buffer-gas (He) in preparation trap
- Well-controlled conditions

🔵 buffer-gas (He)

🔴 contaminant ions

🟢 Ions of interest



How to measure (precisely) masses ?

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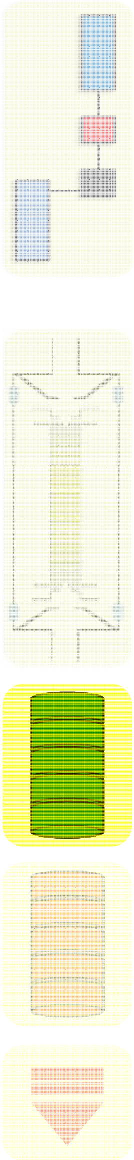
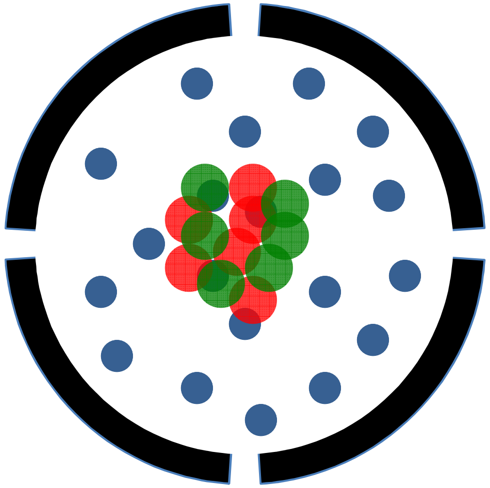
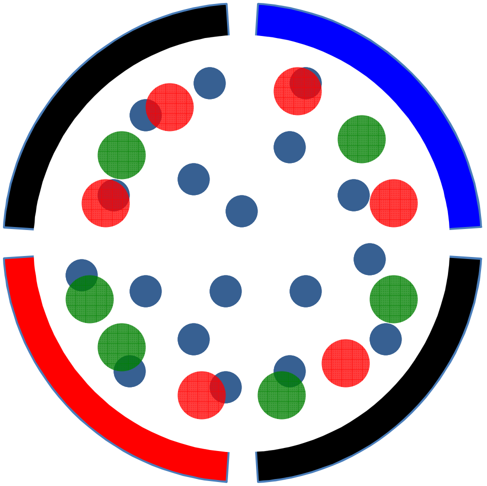
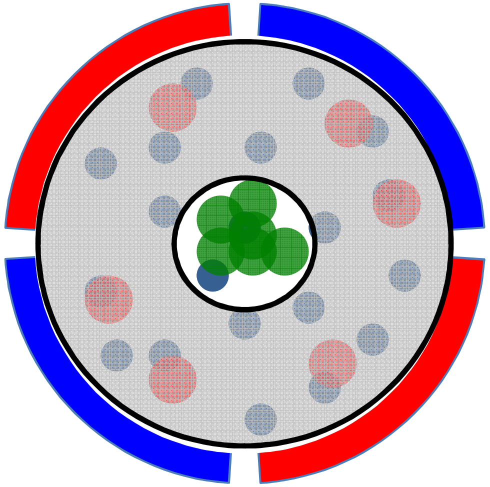






- Dipolar excitation at magnetron frequency (≈ mass independent)



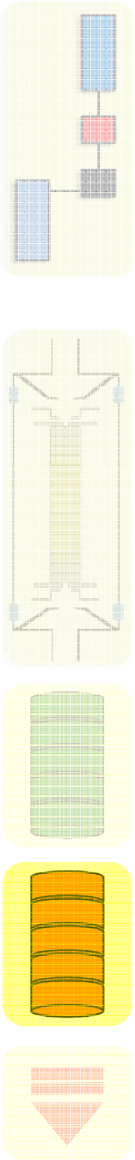
- Quadrupolar excitation at the cyclotron frequency
  mass selective recentering
  large bandwidth → resolving power ~10^5
  (to separate isobars)

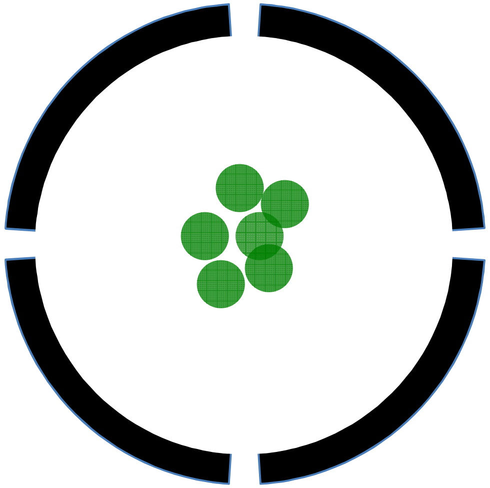
- Ejection of the ions through a diaphgram

G. Savard *et al.*, Phys. Lett. A 158 (1991) 247.

How to measure (precisely) masses ?

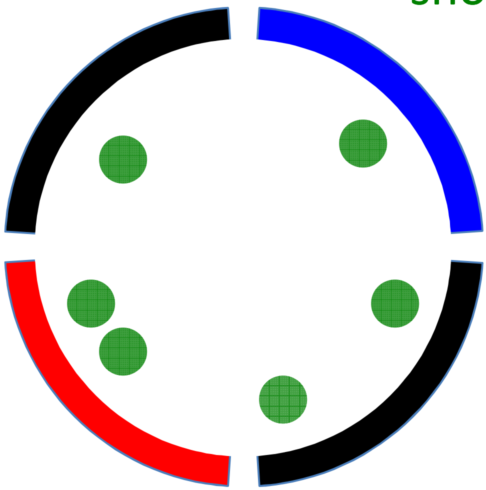
4- mass measurement → measurement Penning trap





- Dipolar excitation at cyclotron frequency mass selective
  → Larger radius

short bandwidth
→ resolving power ~$10^{7\text{-}8}$
(to measure the mass)



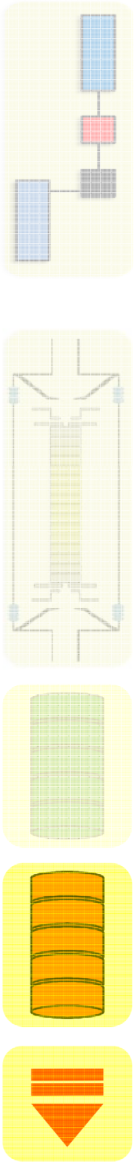
In practice :
-frequency scan around ω_c
- ejection of the nuclei
- measurement of their time-of-flight

When $\omega_c = \frac{q}{m} B$ → nuclei at the larger radius

→ Smaller TOF

How to measure (precisely) masses ?

4- mass measurement → measurement Penning trap



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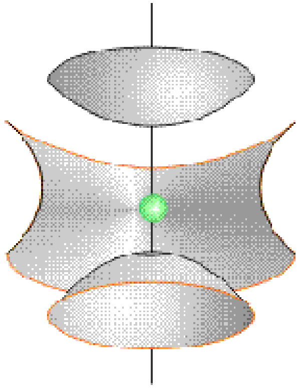
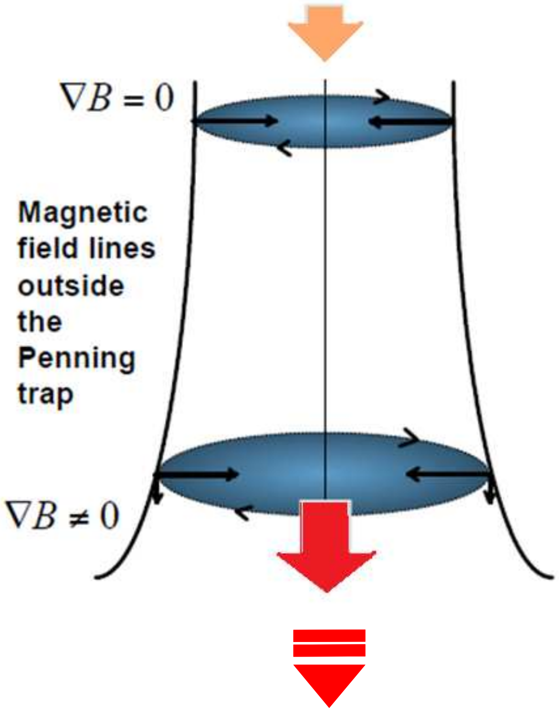


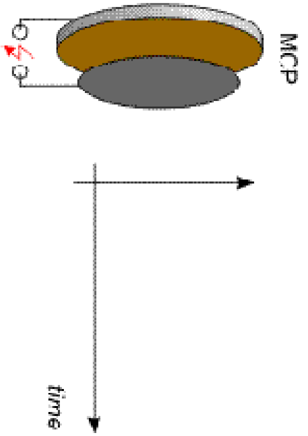
Ions from the Penning trap



orbital energy

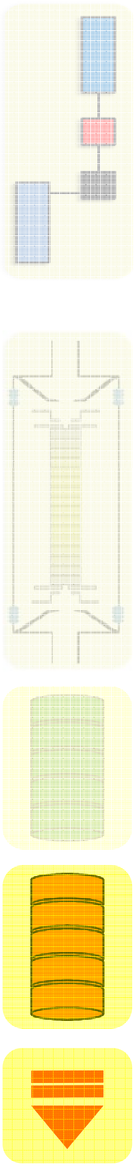
magnetic field gradient outside the PT converts any radial energy into axial energy

axial energy → higher velocity → smaller TOF

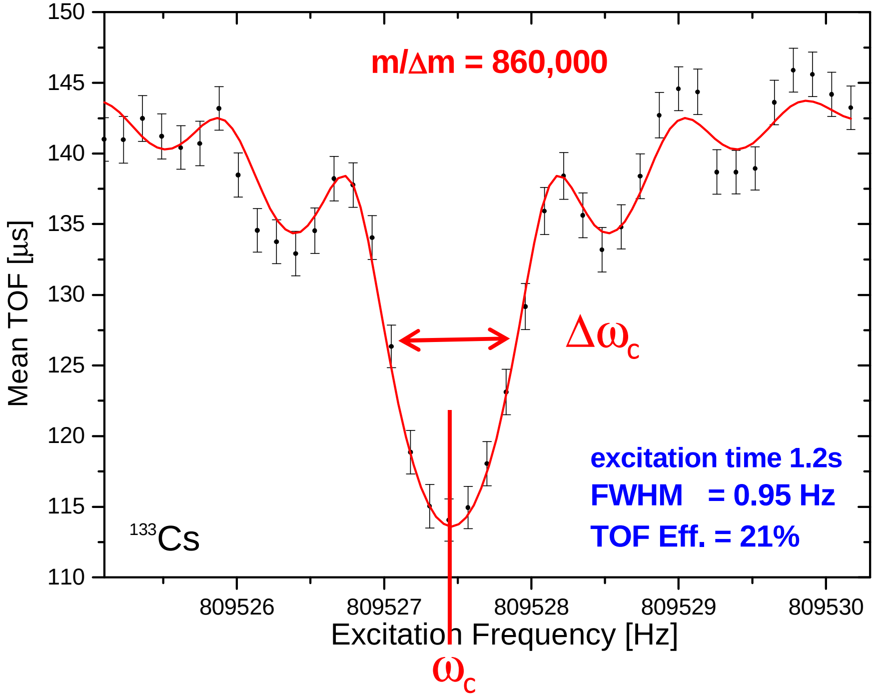


How to measure (precisely) masses ?

4- mass measurement → measurement Penning trap



measurement trap



m/Δm = 860,000

excitation time 1.2s
FWHM = 0.95 Hz
TOF Eff. = 21%

- Each point corresponds to an excitation at a given frequency

- Minimum TOF → ω_c

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

  →need to know B with the same precision…

- in practice, unknown masses are always measured relative to known reference(s)

$$\frac{\omega_{c,ref}}{\omega_{c,unknown}} = \frac{m_{unknown} - m_e}{m_{ref} - m_e} \sim \frac{m_{unknown}}{m_{ref}}$$

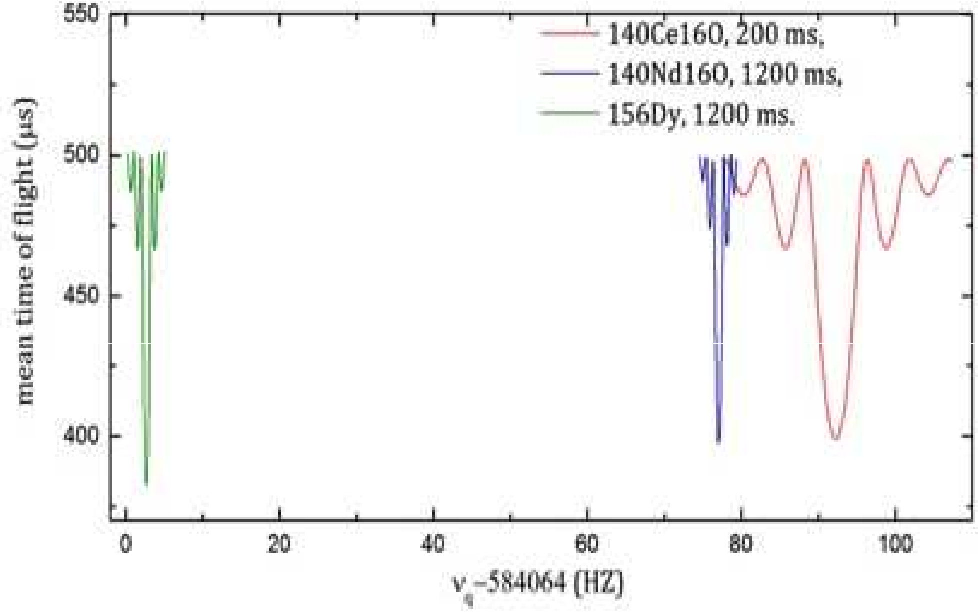
-resolving power : $R = \frac{m}{\Delta m} = \frac{\Delta\omega_c}{\omega_c}$

- For each point, the nucleus is excited during a time T_{exc}

- $$\Delta\omega_c = \frac{1}{T_{exc}}$$

  →higher precision = longer excitation time

4. Results

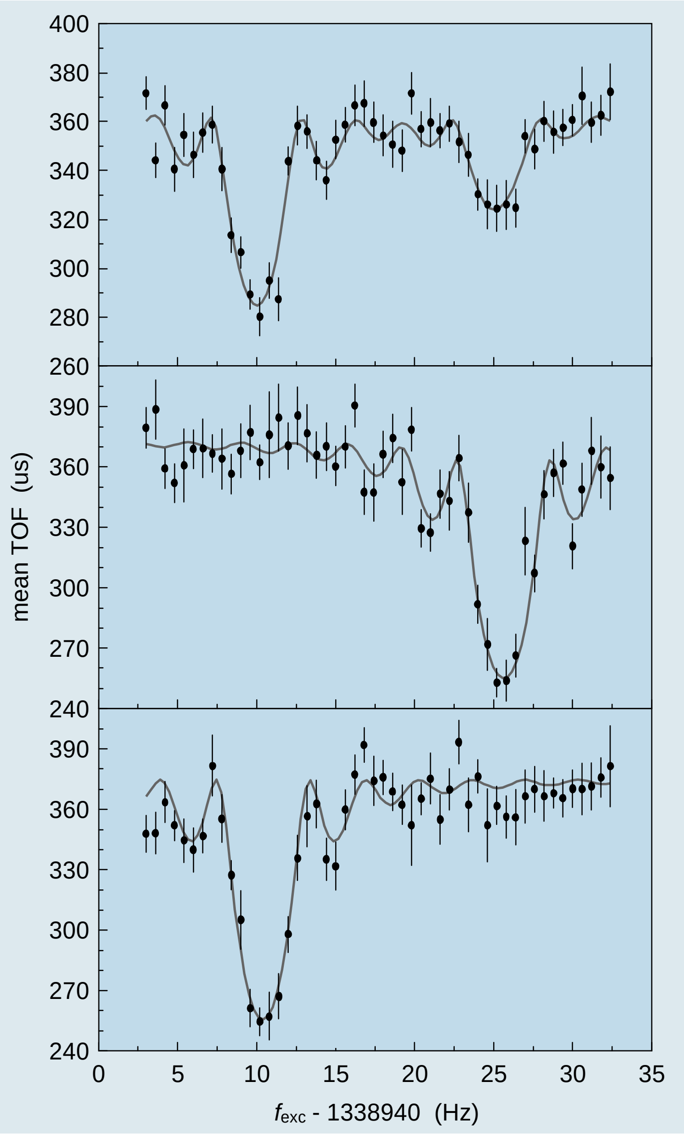


EL	frequency ratio(ν_{ref}/ν)	Uncertainty
$^{140}Ce+^{16}O$	1.1730177877	1.9E-08
$^{140}Nd+^{16}O$	1.1730486010	2.5E-08
^{156}Dy	1.1731977902	2.5E-08

*The reference ion is $^{133}Cs^+$ in all cases.

The line-width of the resonance curve depends on the excitation time (T_q) of the quadrupolar excitation R~ T_q

Questions ?



1) What are these two resonances observed when measuring the mass of ^{68}Cu?

the ground state and… an isomeric state

2) Which one is the ground and the isomeric state? Why?

ground state = lowest mass → higher frequency

3) What is the observed resolving power?

$R = \omega/\Delta\omega = 1338940/5 \sim 2.7 \cdot 10^5$ → ~254 keV

4) What was the excitation T_{exc} time to get this line width?

$\Delta\omega = 5\,Hz$ → $T_{exc} \sim 200\,msec$

5) The reference ions was ^{85}Rb with mass

$m_{85,Rb}$ = 84,911789732(14) u.

The measured frequency ratio was

0,800000818(20) for ^{68g}Cu

0,800009879(19) for ^{68m}Cu.

Calculate for both states the mass excess in keV

(ME = $(m - A)$u ; 1u=931.494028 MeV)

$m(^{68}Cu_{gs}) = R^*m(^{85}Rb) = 67.929610959\ u$

→ ME_gs=-65.5669 MeV

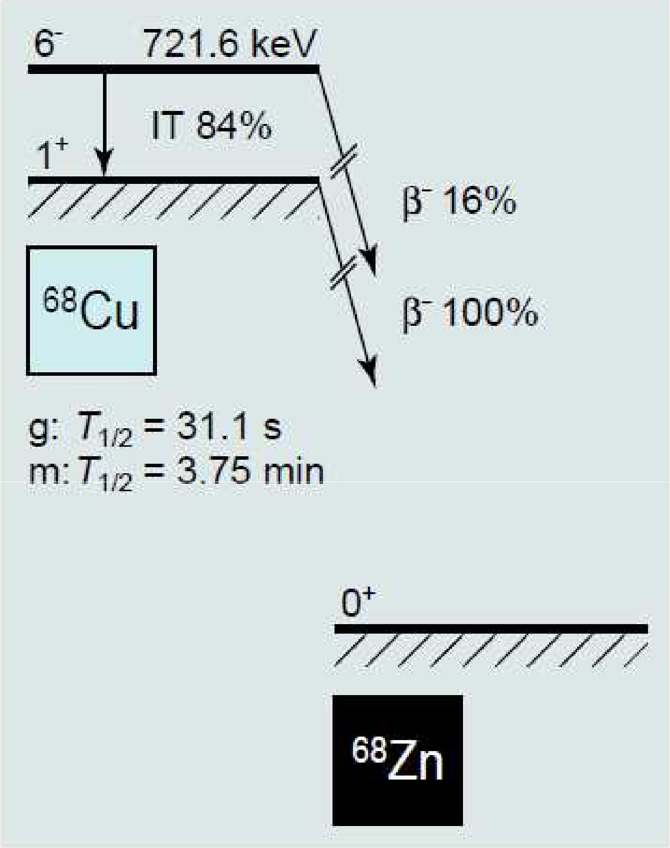
$m(^{68}Cu_{iso}) = R^*m(^{85}Rb) = 67.930380340\ u$

→ ME_iso=-64.8503 MeV

6) What is the excitation energy of the isomeric state?

E_{exc} = ME_iso-ME_gs=717 keV

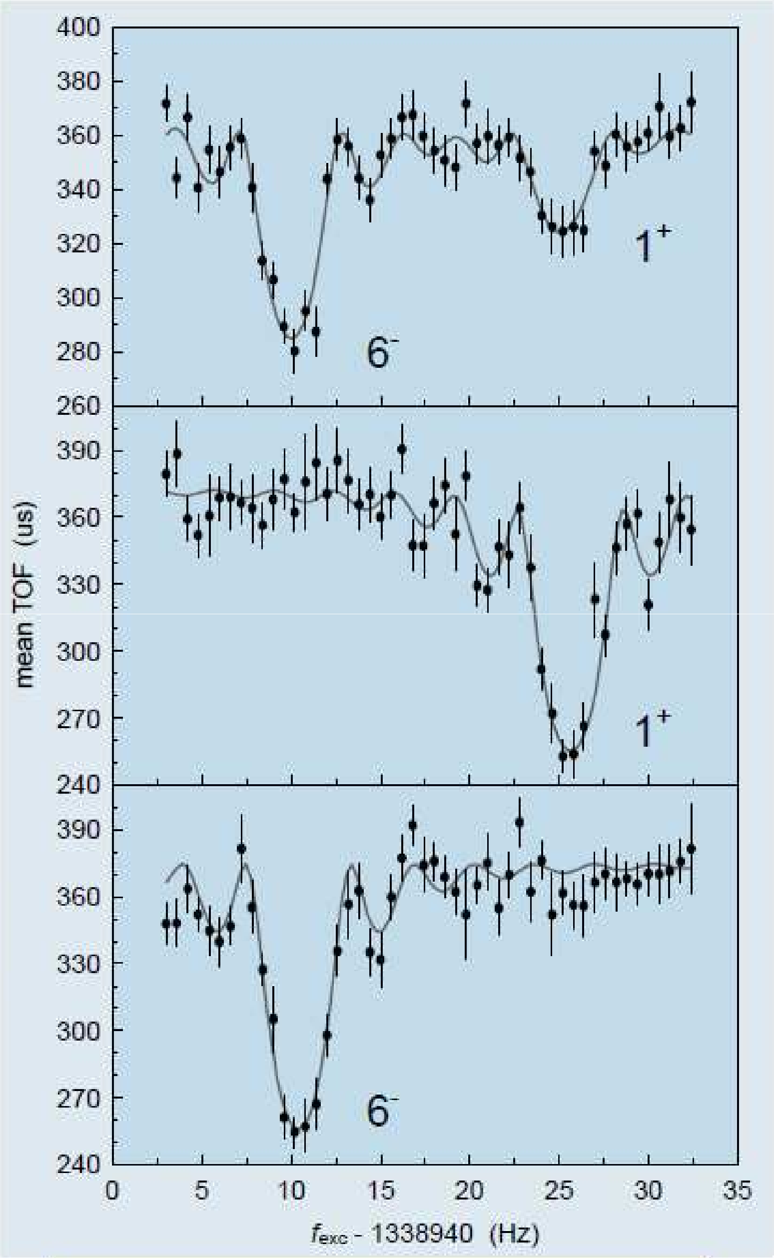
Isomerism in ^{68}Cu:



as produced by ISOLDE

isolation of the 1^+ ground state

isolation of the 6^- isomeric state



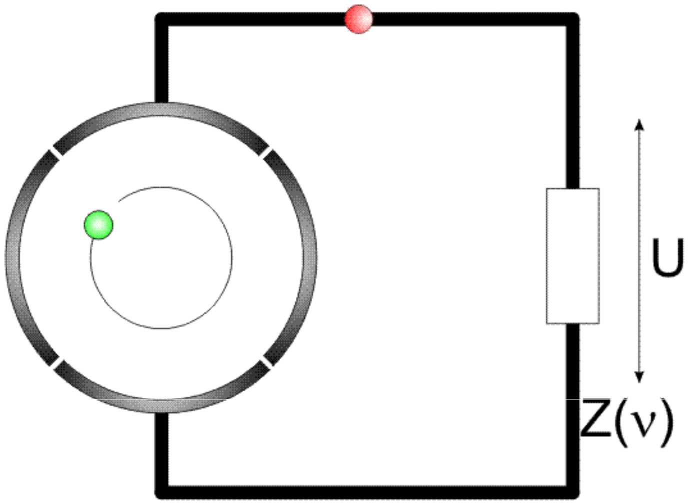
Resolving power of excitation: $\boldsymbol{R} \approx \mathbf{10^7}$

⇒ Population inversion of nuclear states

⇒ Preparation of an isomerically pure beam

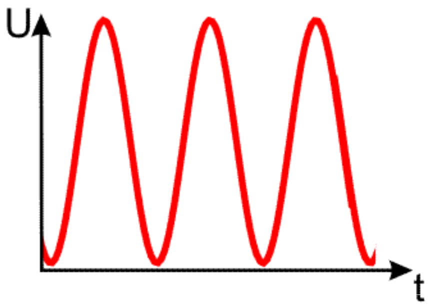
How to measure (precisely) masses ?

The TOF-ICR technique is very powerfull but…. it is a destructive method !
→ to detect a ion, you have to extract it from the trap….



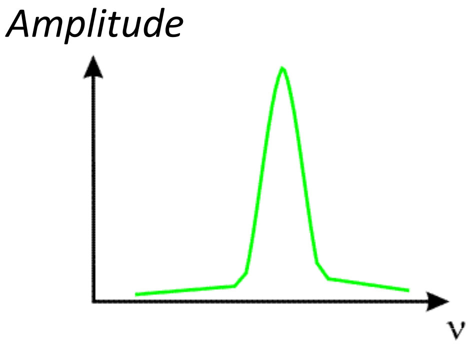
induced image current
read through tuned
tank circuit

ion signal



very small signal ~fA

mass/frequency spectrum

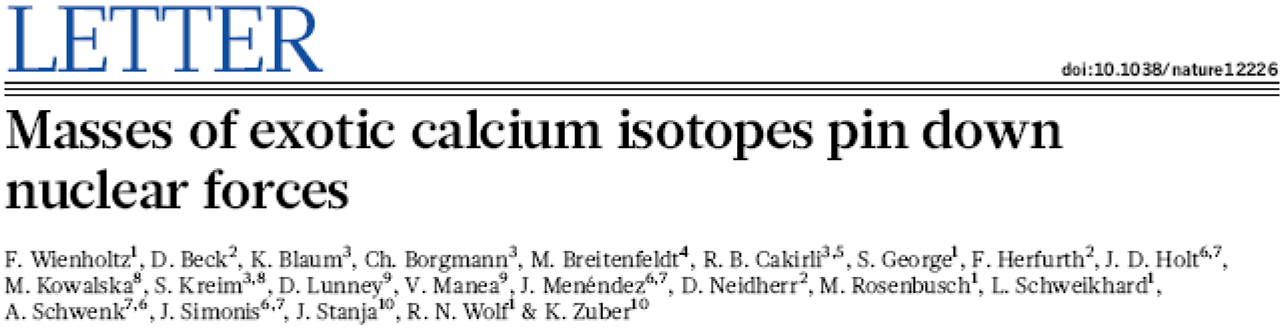


„FT-ICR“
Fourier-**T**ransform-
Ion **C**yclotron **R**esonance

Advantage : need only one ion to measure a mass whereas ~300 are needed with the classical TOF-ICR technique

But: very small signal → noise → delicate electronics with very high Q factor (use of cryogenic technics…)

Multi-reflection time-of-flight and Penning-trap mass spectrometry



LETTER

doi:10.1038/nature12226

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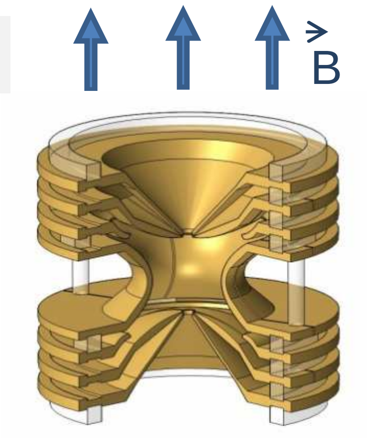
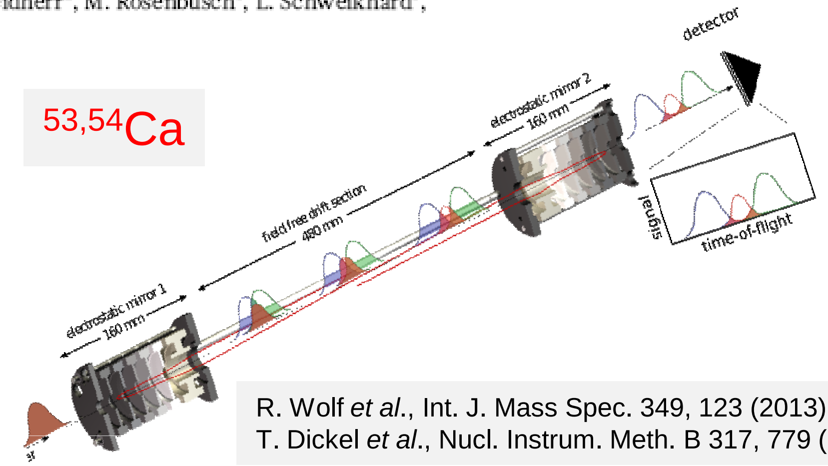
F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

^{51,52}Ca



^{53,54}Ca



R. Wolf *et al*., Int. J. Mass Spec. 349, 123 (2013)
T. Dickel *et al*., Nucl. Instrum. Meth. B 317, 779 (2013)

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

ISOLTRAP (CERN), TITAN (TRIUMF)

MR-TOF-MS - few words

Dedicated poster → P. Chauveau

i- Principle

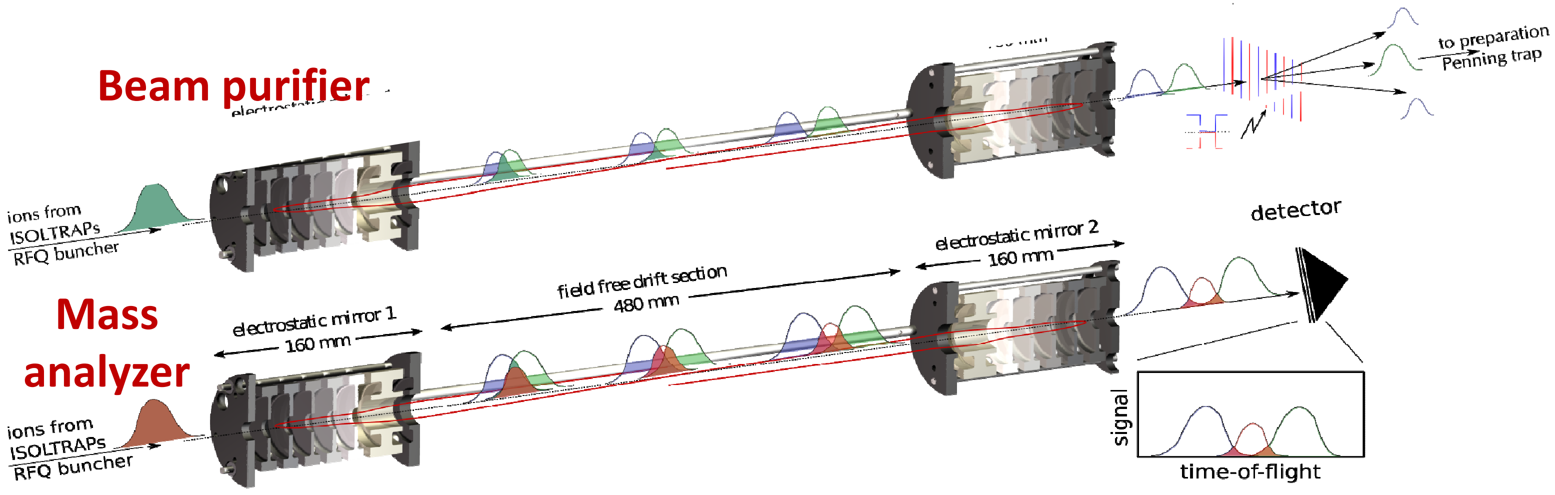
Time-of-Flight separation in a linear trap

Nuclei extrated with the same energy → ΔM ↔ Δv

^{132}Sn : mass = 131.9178157 → v = 0.020948$\boxed{6}$ cm/ns
^{132}Sb : mass = 131.9144669 → v = 0.020948$\boxed{8}$ cm/ns
@ 5 keV

In 10 msec →

- Flight pass : 2 km ! →multi reflections (~4000) in a "linear trap"
- Δ_L : 2 cm
- Δ_TOF : 100 ns

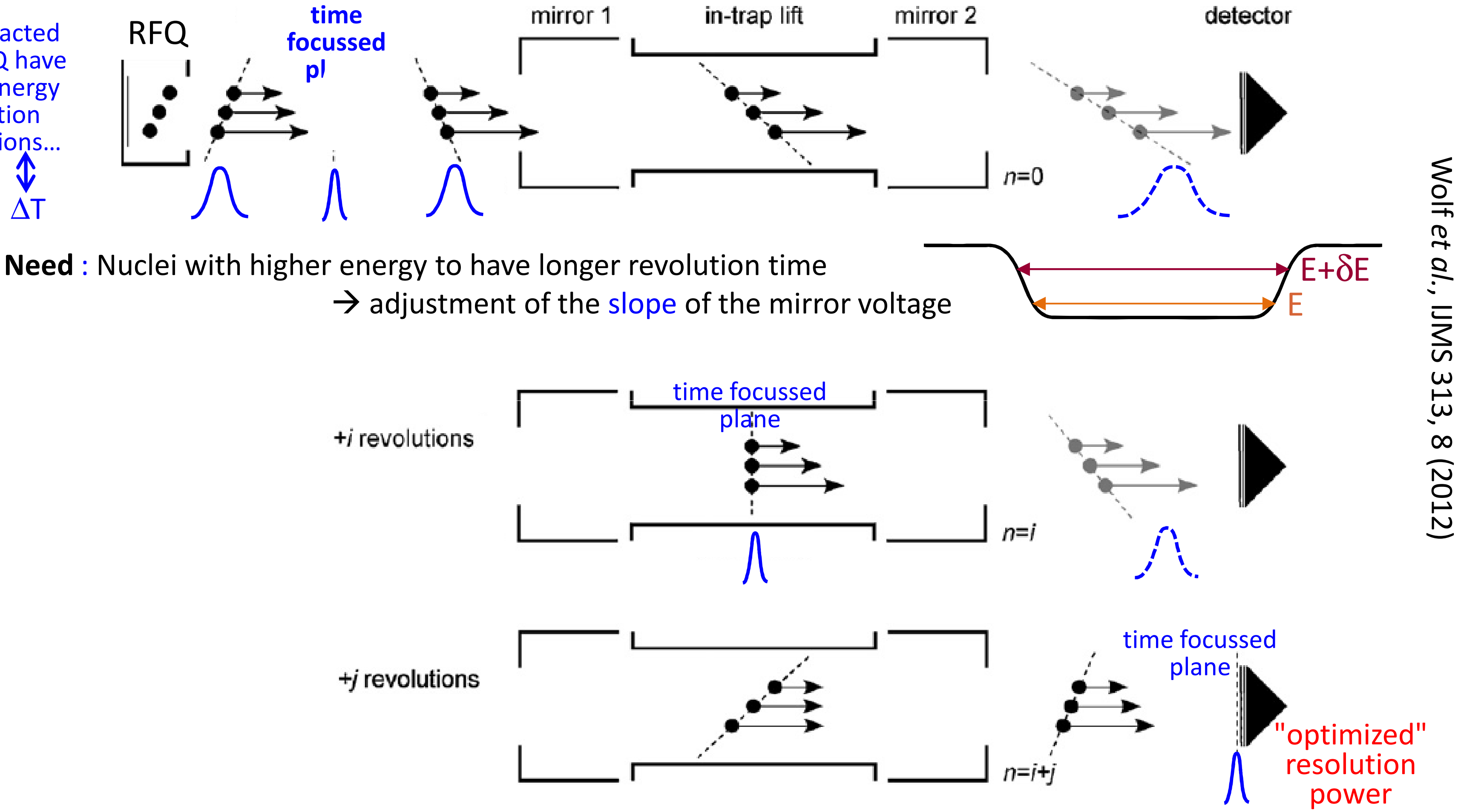


MR-TOF-MS - few words

ii- Developments

ToF focussing

Energy spread → need "time focussing"



Ions extracted from RFQ have (small) energy and position distributions...

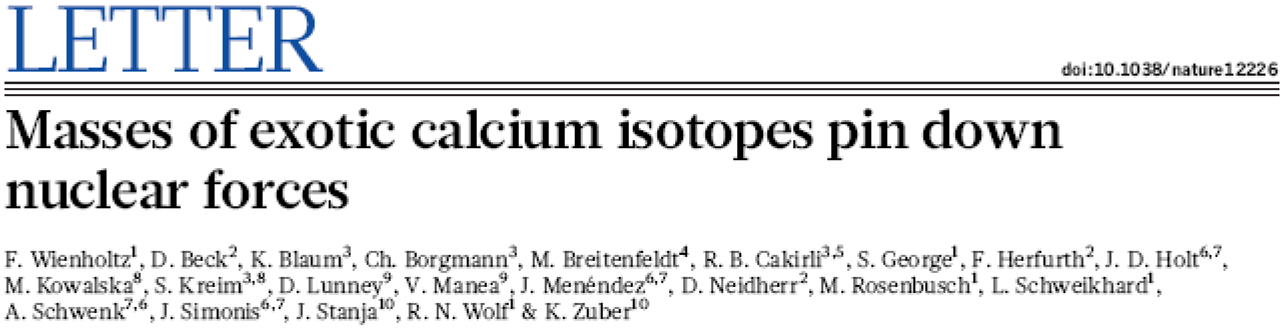
Need : Nuclei with higher energy to have longer revolution time
→ adjustment of the slope of the mirror voltage

"optimized" resolution power

Wolf *et al.*, IJMS 313, 8 (2012)

Generalization : Mirrors optimization to have a Flight time independant from :
- energy
- transverse position
- divergence

Multi-reflection time-of-flight and Penning-trap mass spectrometry



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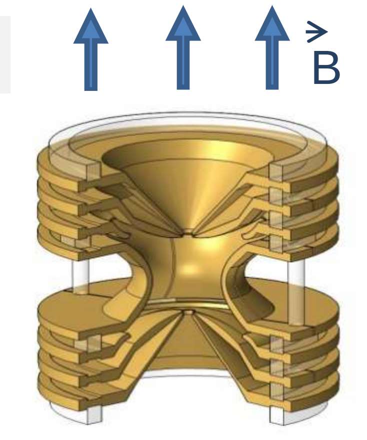
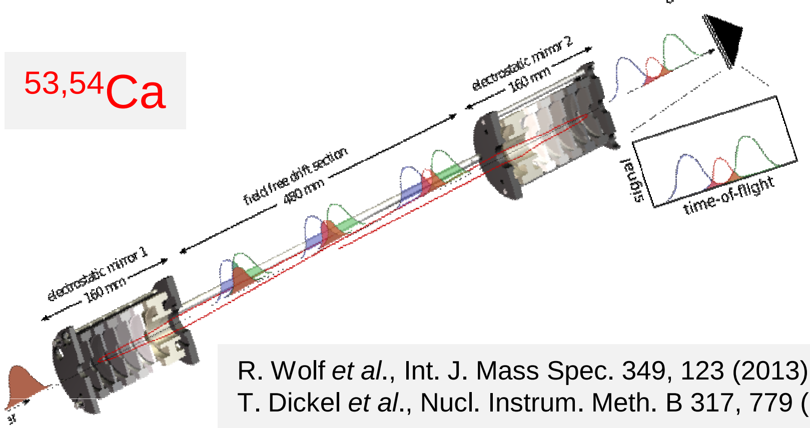


^{53,54}Ca



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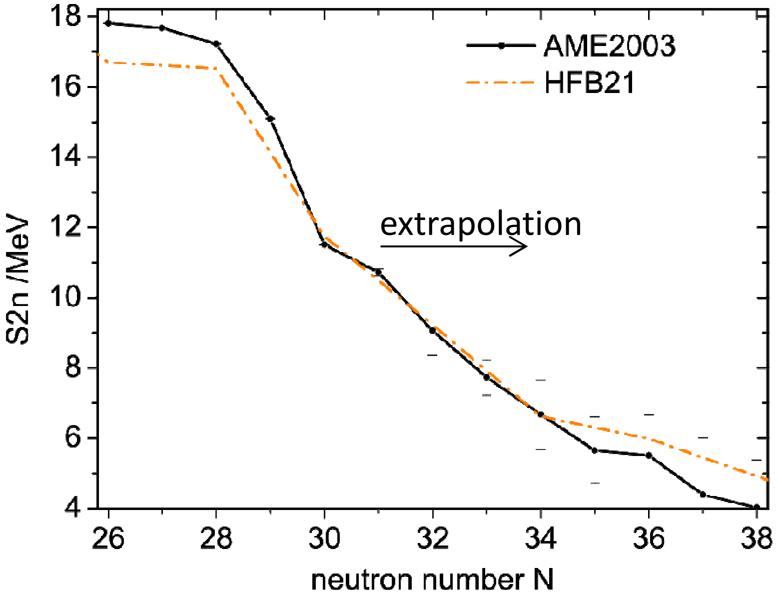
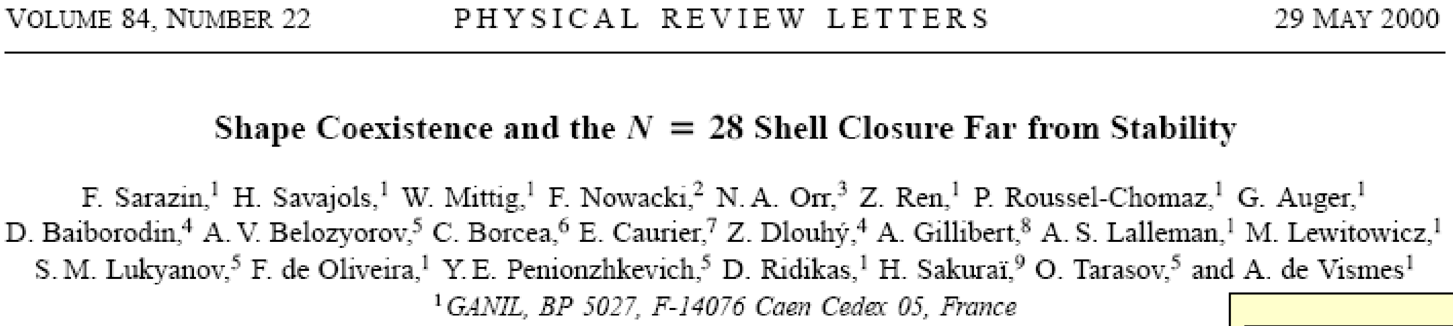


ISOLTRAP (CERN), TITAN (TRIUMF)

Mass measurements around N=28



VOLUME 84, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY 2000

Shape Coexistence and the $N = 28$ Shell Closure Far from Stability

F. Sarazin,[1] H. Savajols,[1] W. Mittig,[1] F. Nowacki,[2] N. A. Orr,[3] Z. Ren,[1] P. Roussel-Chomaz,[1] G. Auger,[1]
D. Baiborodin,[4] A. V. Belozyorov,[5] C. Borcea,[6] E. Caurier,[7] Z. Dlouhý,[4] A. Gillibert,[8] A. S. Lalleman,[1] M. Lewitowicz,[1]
S. M. Lukyanov,[5] F. de Oliveira,[1] Y. E. Penionzhkevich,[5] D. Ridikas,[1] H. Sakuraï,[9] O. Tarasov,[5] and A. de Vismes[1]
[1] *GANIL, BP 5027, F-14076 Caen Cedex 05, France*

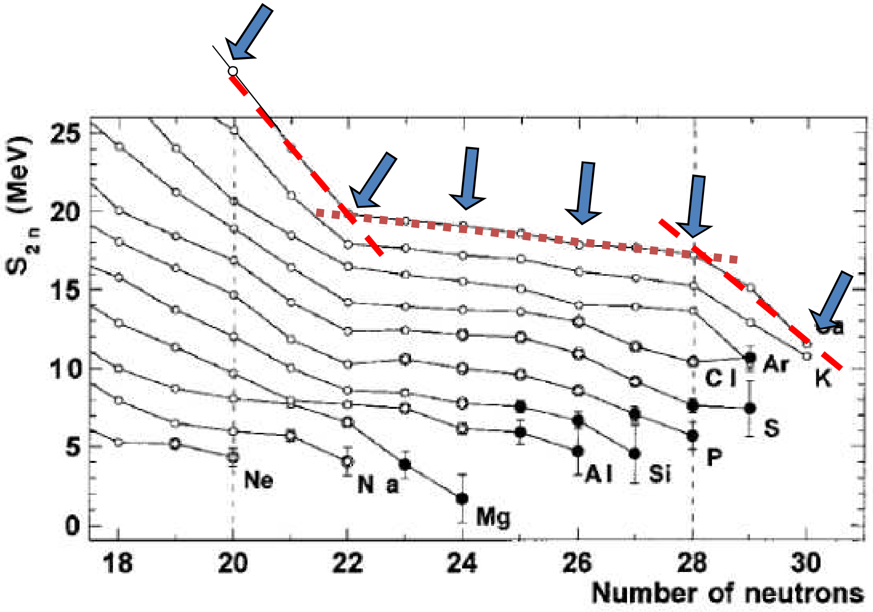
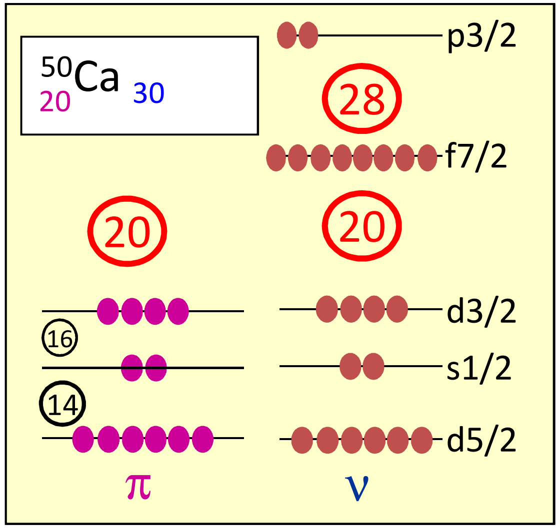


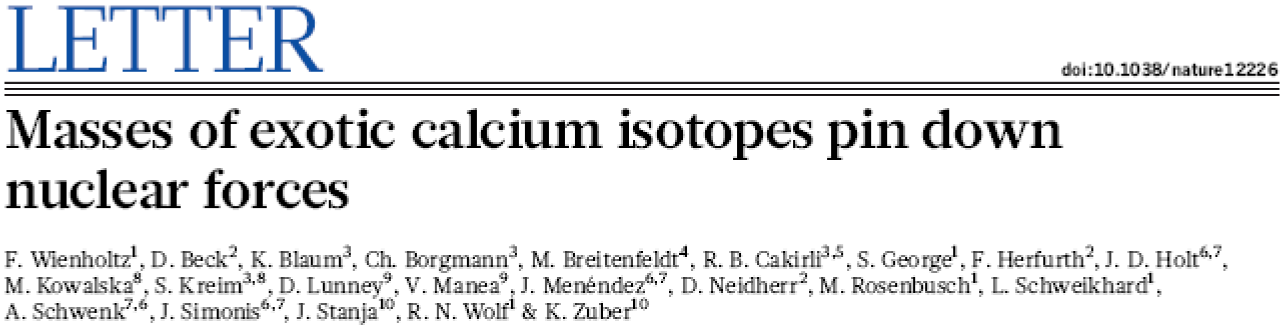
FIG. 1. Experimental S_{2n} values in the region of the $N = 20$ and 28 shell closures. The circles correspond to values from Ref. [13], the bold circles to values for which the precision was improved, and the filled circles to masses measured for the first time (Table I).



- change in the slope of the S_{2n} is an indication of a shell closure (or more generally, a change in the shell structure)

→observed at N=20 and N=28 in Ca isotopes

Multi-reflection time-of-flight and Penning-trap mass spectrometry



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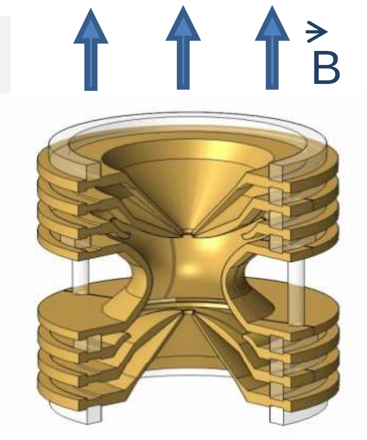
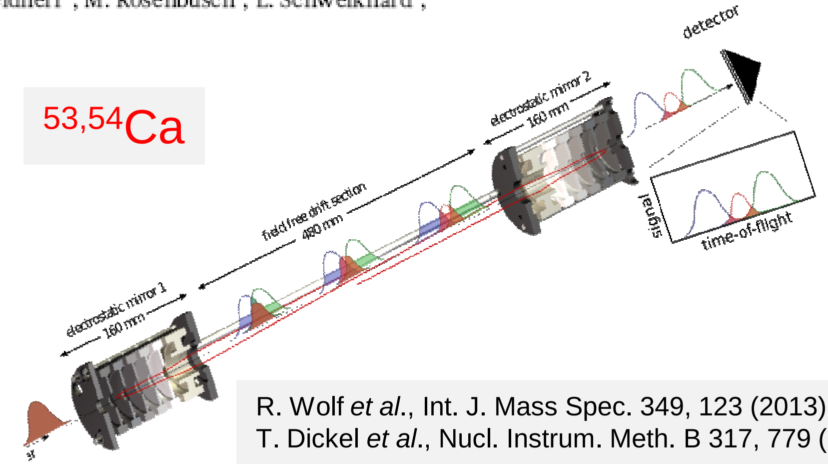
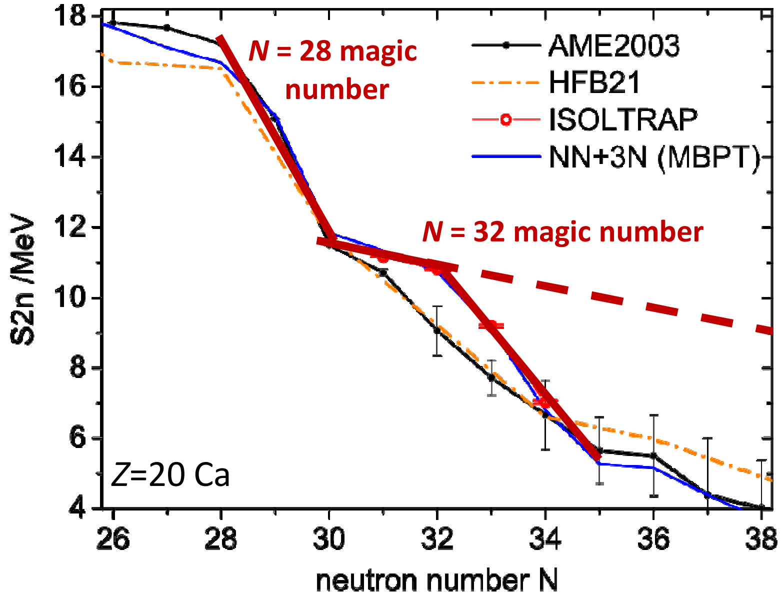


^{53,54}Ca



R. Wolf *et al*., Int. J. Mass Spec. 349, 123 (2013)
T. Dickel *et al*., Nucl. Instrum. Meth. B 317, 779 (2013)

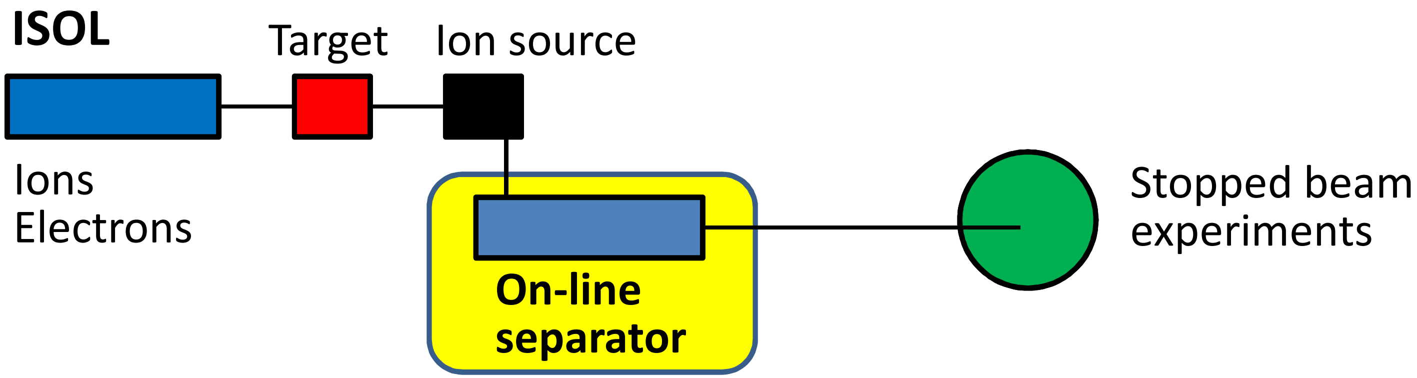
- Production rates of ~10 ions/s
- Mass measurements via S_{2n} establish new magic number at *N* = 32
- Correct prediction from 3N-forces (A. Schwenk *et al.*, TUD)



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

ISOLTRAP (CERN), TITAN (TRIUMF)

Purification of ISOL type RIB



ISOL

Target

Ion source

Ions
Electrons

On-line separator

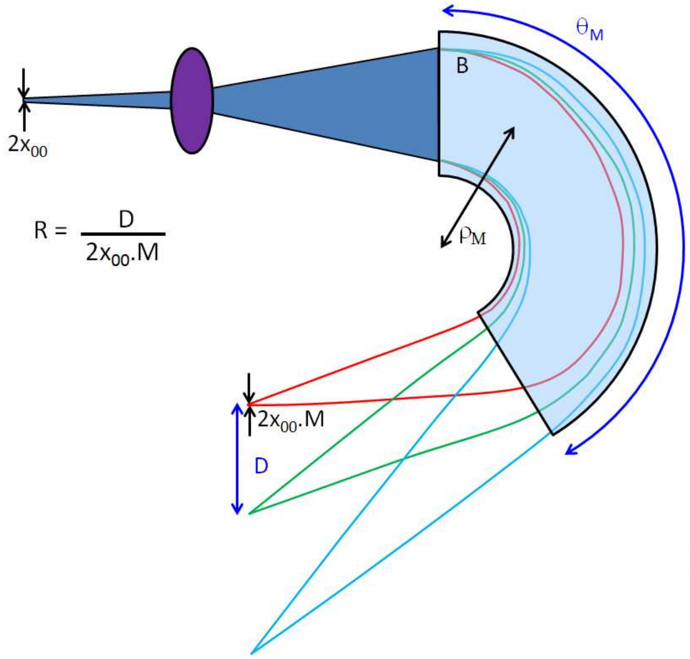
Stopped beam experiments

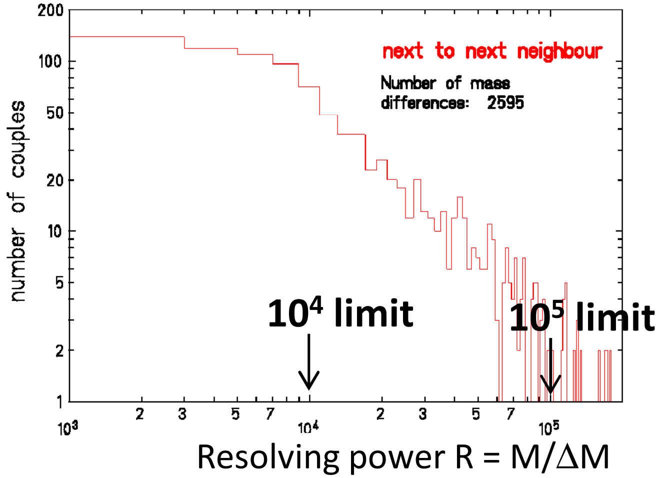
-High Resolution Magnetic Separators (HRS)

- HRS @ ISOLDE
- CARIBU @ TRIUMF

→Resolving power R=ΔM/M ~ 10000

→ not enough to separate all the isobars





New idea : use a double Penning trap to purify **large bunches** of exotic nuclei to obtain totally pure samples and perform precision measurements

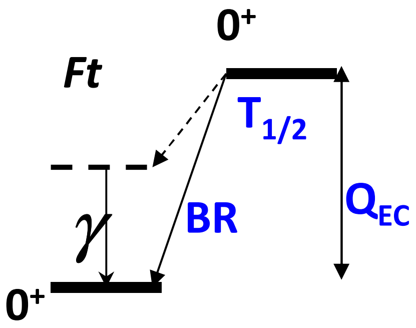
→ PIPERADE project for DESIR/SPIRAL2

Test of the fundamental interactions

dedicated poster → C. Magron

Standard model

- contains all les rules concerning the reactions between quarks and/or leptons, interacting through the electroweak interaction and/or quantum chromodynamics
- depends of a finite number of parameters fixed by experiments



Weak interaction → responsible of the beta-decay

1930 → 1950 : V-A theory, based on experimental observations

transition strenght:
$$f(Z,Wo)t = \frac{K}{g^2_{Vector}\,\langle M_{Fermi}\rangle^2 + g^2_{Axial}\,\langle M_{Gamow\ Teller}\rangle^2}$$

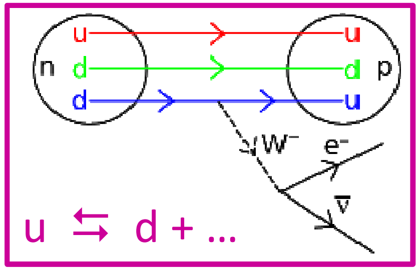
0^+ → 0^+ Fermi transitions

↳ no axial current (selection rules)

$$f(Z,Wo)t = \frac{K}{g^2_{Vector}\,\langle M_{Fermi}\rangle^2} = f(Q_{ec}) * T_{1/2} / BR$$

➢ CVC hypothesis (Vector Curent Conservation) → *ft = constante*

↳ g_{Vector} is identical for **all** β-transitions



Cabibbo-Kobayashi-Maskawa
$$\begin{pmatrix} u' \\ s' \\ d' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} u \\ s \\ d \end{pmatrix}$$

*quarks are eigenstates of the strong interaction, **not** of the weak interaction*

➢ Unitarity of CKM matrix : $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

↳ relation between V_{ud} and ft for the Fermi transitions :

$$|V_{ud}|^2 = \frac{2\,\pi^3\,\ln 2}{g_\mu^{\,2}.ft.|M_{if}|^2}$$

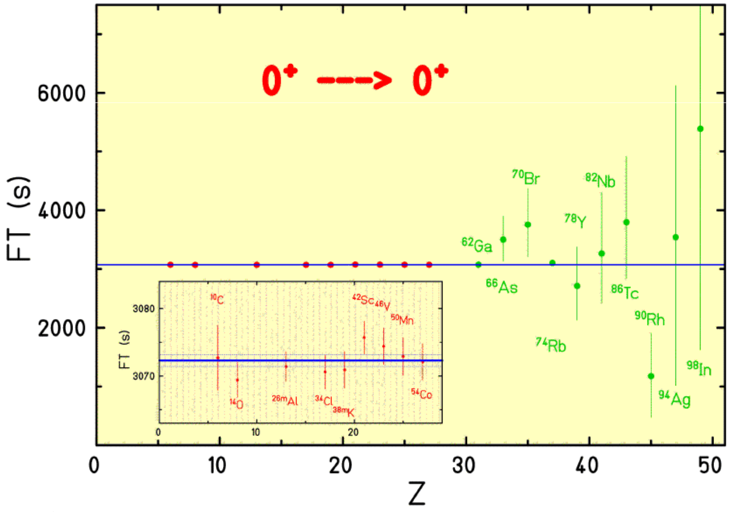
Test of the fundamental interactions

Study of the $0^+ \rightarrow 0^+$ Fermi transitions

- ↳ Verification of the CVC hypothesis by comparing ft for different nuclei
- ↳ Extraction of V_{ud}
- ↳ Verification of the unitarity of the CKM matrix

Needed precisions

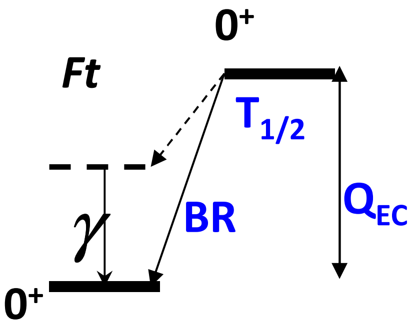
- overall precision : Ft = (3072.08 ± 0.79) s for 13 transitions $\Rightarrow$ $1.3 * 10^{-4}$



- *Ft = 3072.08(79) s*
- V_{ud} = 0.97425(22)
- $\sum V_{ui}$ = 0.99995(61)

$\Rightarrow$ individual mesurements $< 10^{-3}$

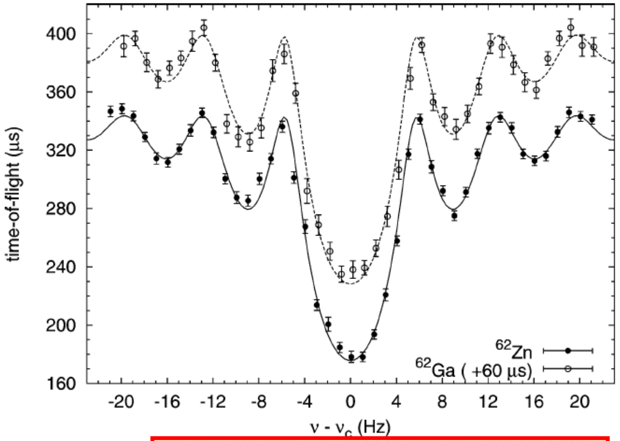
- f: $f(Q_{EC})$ $\rightarrow$ $\Delta Q < 2 * 10^{-8}$ $\rightarrow$ < 1keV
- $T_{1/2}$: $\Delta T << 10^{-3}$
- BR: $\Delta BR < 10^{-3}$

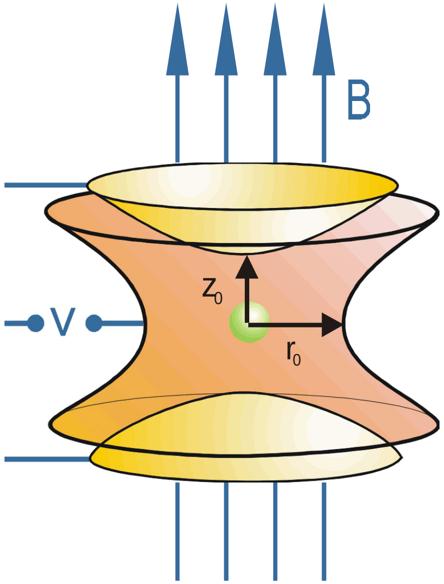


→ Study on exotic nuclei of very high purity

Test of the fundamental interactions

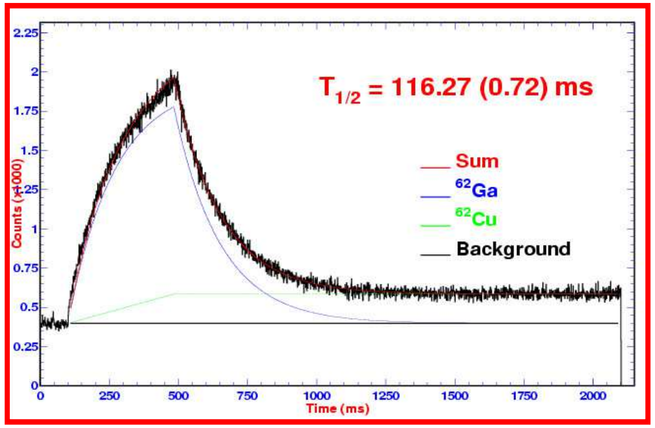
- **JYFLTRAP**

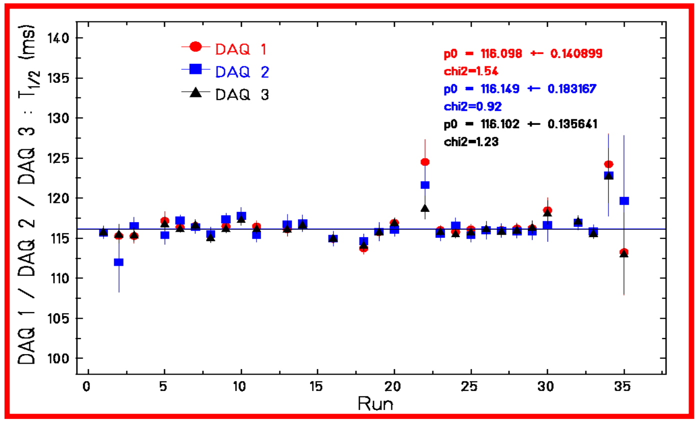




Q_{EC} = (9181.07 ± 0.54) keV

T. Eronen et al., 2006





$T_{1/2}$ = (116.12 ± 0.15) ms

G. Canchel et al., 2005

Purification of ISOL type RIB

dedicated poster → M. Aouadi

PIPERADE @ DESIR-SPIRAL2

Goals:

- Very high Resolving power (> 10^5) to clean isobars not cleaned by the HRS + isomers

  → Penning traps can reach a resolution (up to 10^8) **but** are limited in terms of number of ions

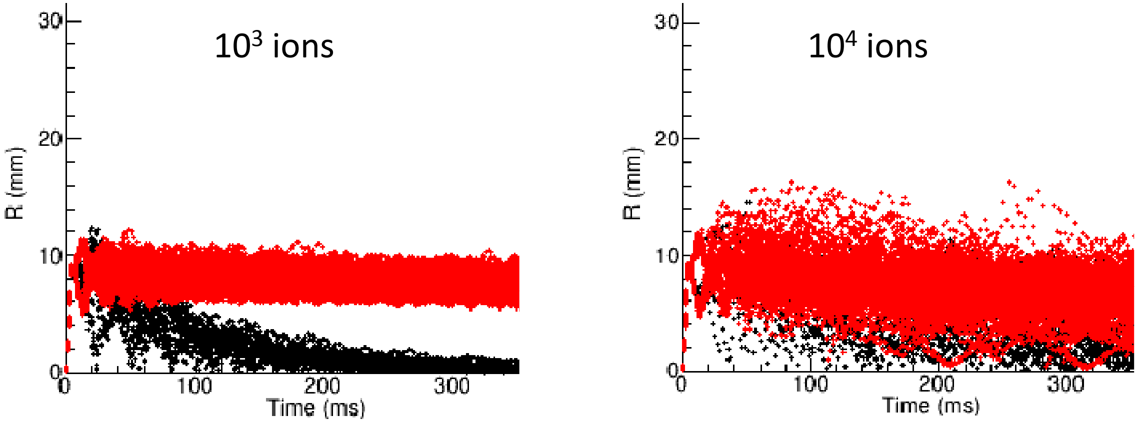
- Purifying very large samples (accept 10^5 to 10^6 per bunch → 10^7 to 10^8 pps)

Increasing the number of ions makes the re-centering inefficient

Additional potential created by the cloud itself

→ frequency-shifts
→ peak broadening
→ screening effects

90% ^{136}Te, 10% ^{136}Sb
P = 10^{-4} mbar   B = 7T
r_0 = 20 mm



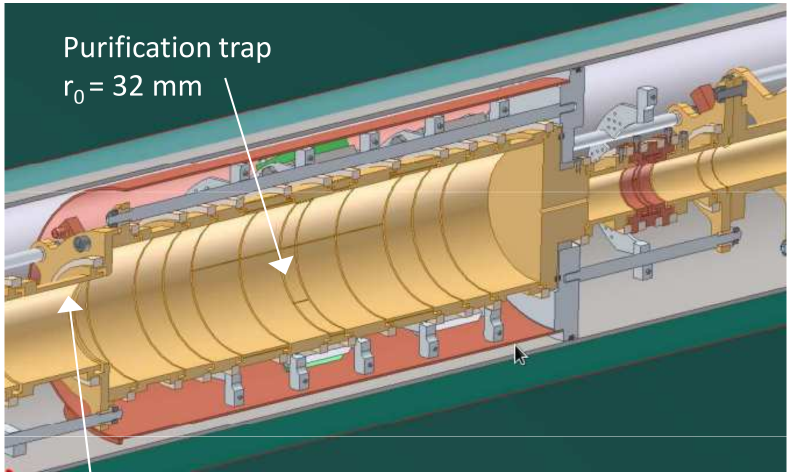
SIMBUCA code, *S. Van Gorp et al., NIM A 638, 192200 (2011)*

Purification of ISOL type RIB

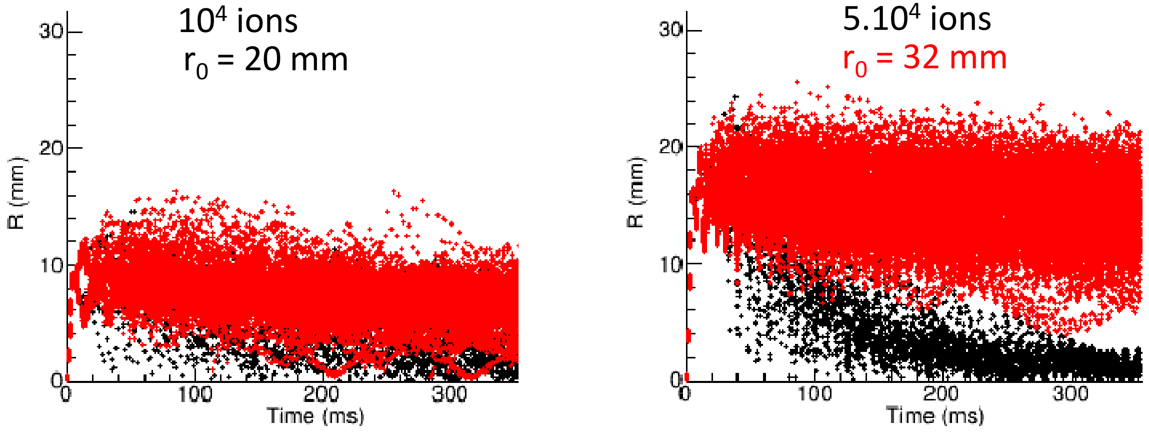
PIPERADE @ DESIR-SPIRAL2

Solutions

- Large inner radius (32 mm) and length (~10 cm)
  - → Decrease the cloud density
  - → Limit space charge effects

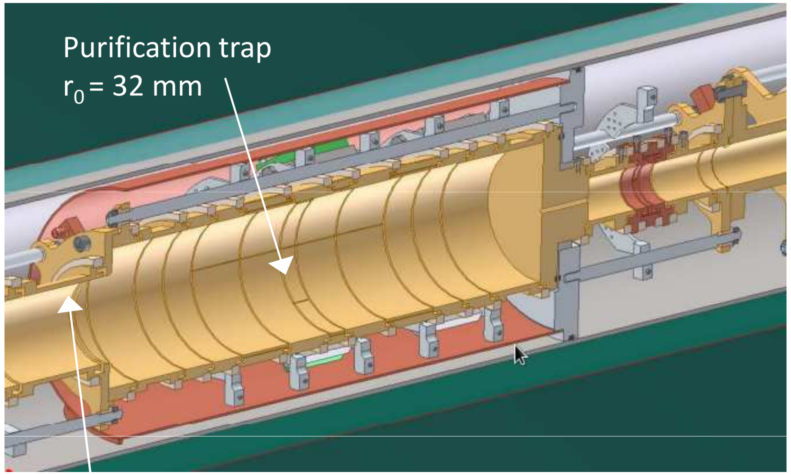


90% ^{136}Te, 10% ^{136}Sb
P = 10^{-4} mbar B = 7T



Purification of ISOL type RIB

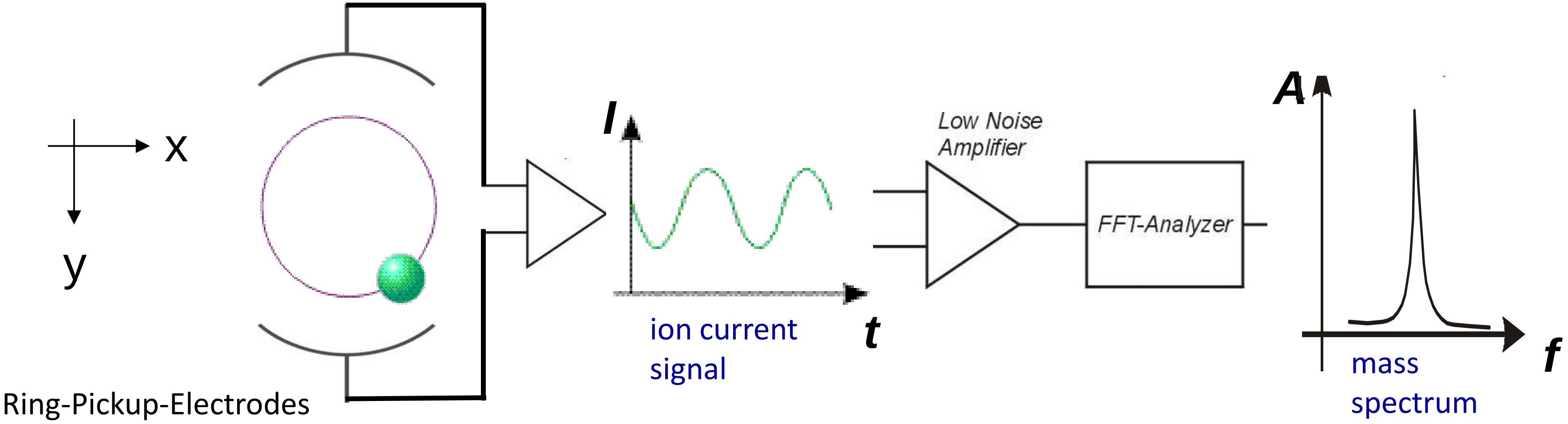
PIPERADE @ DESIR-SPIRAL2



Solutions

- Large inner radius (32 mm) and length
  → Decrease the cloud density
  → Limit space charge effects
- Broad-band FT-ICR detection
  → Identify online abundant contaminants

„FT-ICR“ : Fourier Transform Ion Cyclotron Resonance

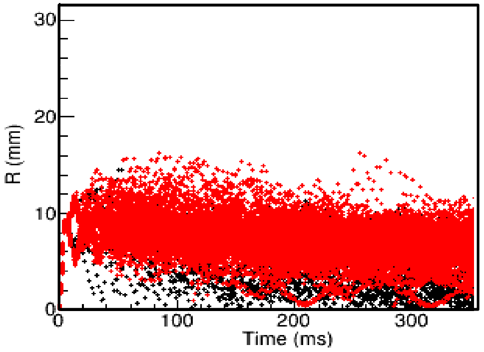


Purification of ISOL type RIB

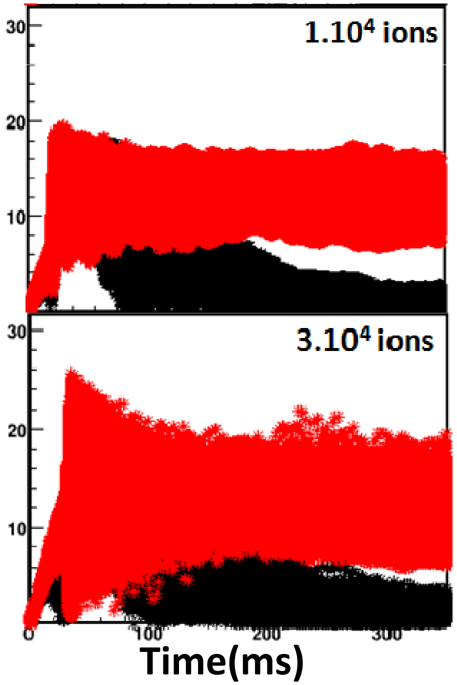
PIPERADE @ DESIR-SPIRAL2

If you know the frequency of the most abundant contaminant…
(thanks to the FT-ICR)

90% ^{136}Te, 10% ^{136}Sb
P = 10^{-4} mbar   B = 7T



With a pre-excitation
at ν+ of contaminant



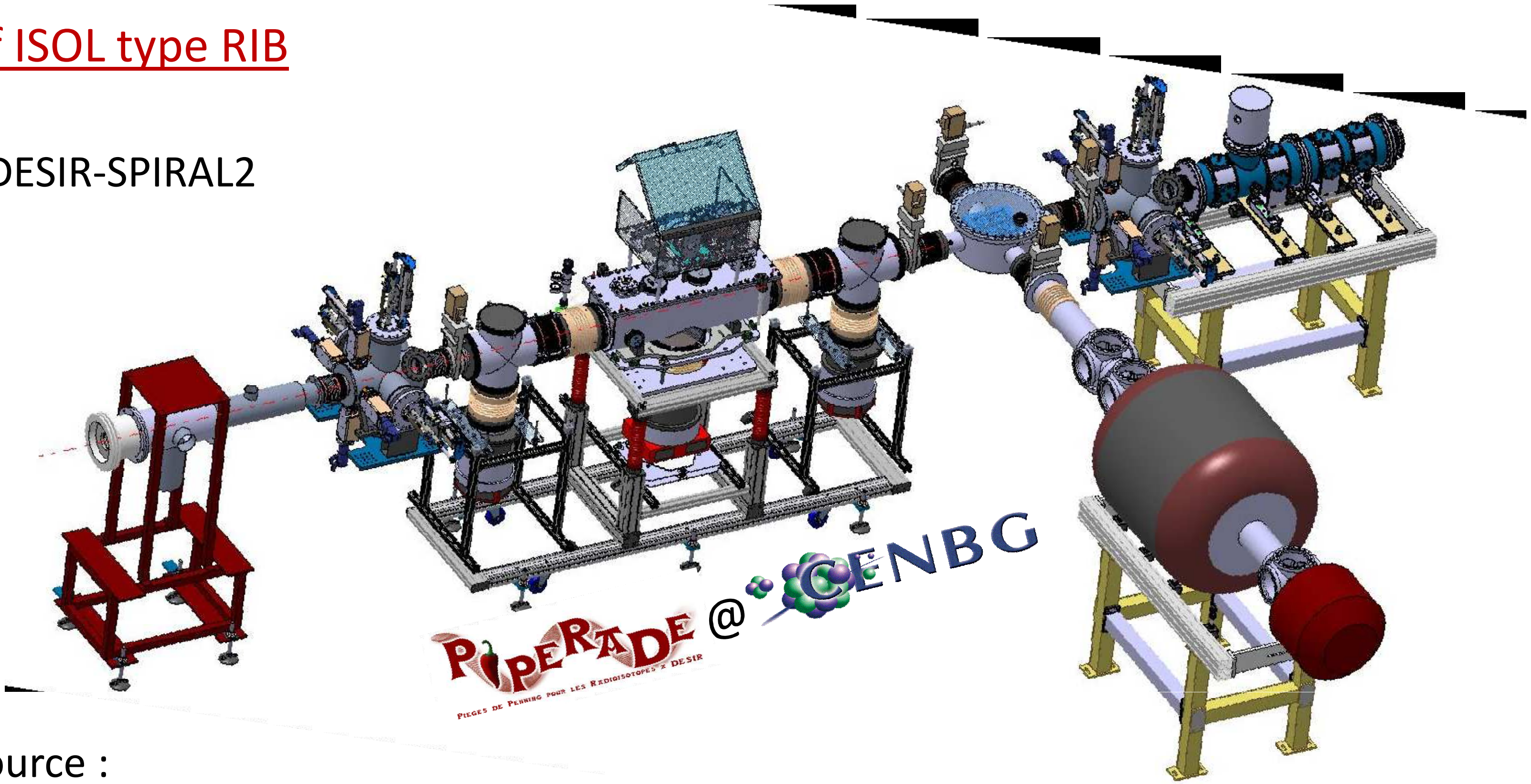
Alternative techniques…

Simulations (MPIK and CENBG) and tests are ongoing to find new separation methods (phase splitting, SIMCO, axial coupling, rotating wall, …)

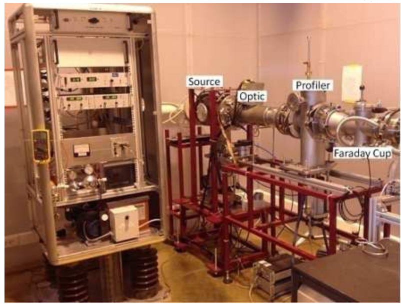
P. Ascher. S. Naimi. A. de Roubin. E. Minava - MPIK. P. Dupré CSNSM

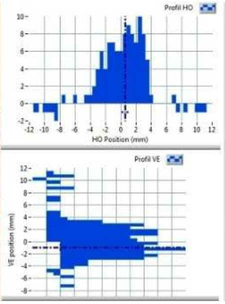
Purification of ISOL type RIB

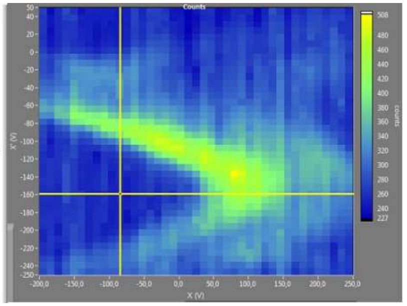
PIPERADE @ DESIR-SPIRAL2



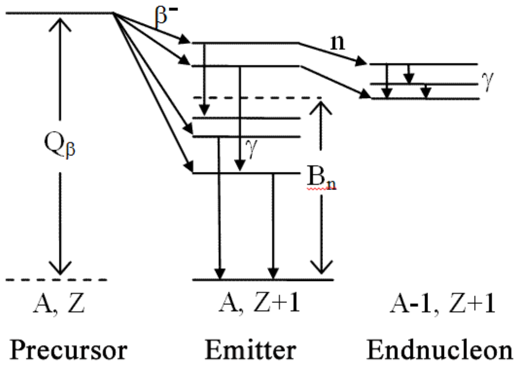
- Febiad Ion source :
  - emittance caracterized
- RFQ-GPIB "*General Purpose Ion Buncher*"
  - on test
- Penning Trap
  - simulations underway
  - mechanical design ready
  - construction end of 2015
  - magnet ordered (delivery expected 06/16)
  - tests@CENBG in 2016/2017







Why Beta-Delayed Neutron Spectroscopy ?



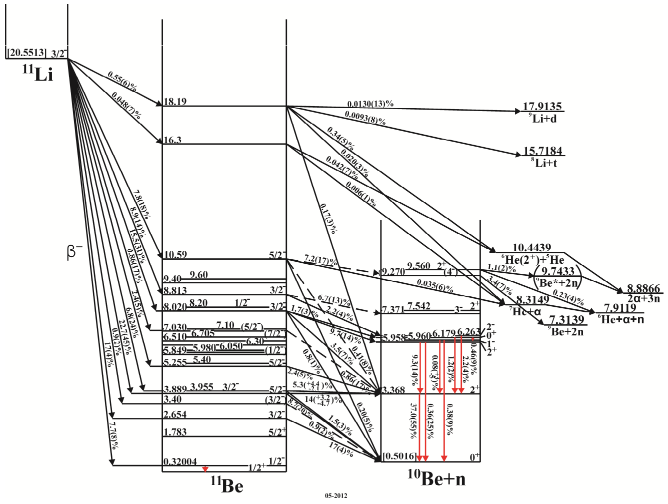
For the most neutron-rich nuclei :

- large Q_β
- small S_n

→ β-delayed neutron emission

Experimental data are needed for :

- astrophysics : r process nucleosynthesis of elements heavier than Fe



- nuclear structure : properties of neutron rich nuclei
  - nuclei at the drip line
  - nuclei at the closed shell
  - …

		needed accuracy
- nuclear energy :	reactor design, performance and safety	
	- delayed neutron fraction → Pn	1-5 %
	- average energy !! → energy spectra	< 20%

but neutrons are always difficult to measure….

Detection of Neutrons

Sub-atomic particles have to interact with their environment to be "detected"
→ ionization

But neutrons are… neutral ☺
→ no Coulomb interaction
→ always an "indirect measurement"

- low energy → capture $n+{}^{3}He \rightarrow {}^{3}H+{}^{1}H$…
  → activation ${}^{56}Fe(n,p) \rightarrow {}^{56}Mn$

- high energy → (in)elastic scattering
  → recoiling particles : p…

Compromises to do on :
- efficiency
- resolution
- threshold

Is it possible to performed beta-delayed neutron spectroscopy…
without detecting the neutrons ??

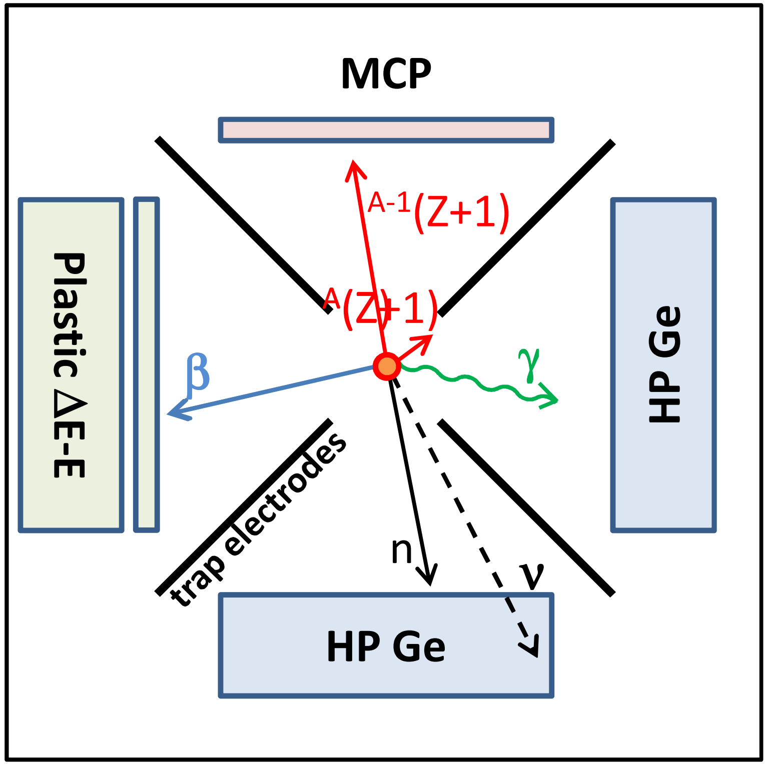
Beta Delayed Neutron Spectroscopy… without detecting neutrons ☺

Principle :

By momentum and energy conservation :
TOF of recoiling $^{A-1}(Z+1)$ ←→ neutron energy

- trap the nuclei as ions
- cool by He gas to ~1mm^3 volume
- ions decay at rest at the trap center
    - β only : slow recoil
    - βn : fast recoil
- trigger on β's seen by plastic
- Measure recoil TOF to MCP

$$^{A}(Z) \rightarrow {}^{A}(Z+1)^{*} + \beta^{-} + \nu$$
$$\hookrightarrow {}^{A-1}(Z+1) + n$$



Mass	Q_β/E_n MeV	HI recoil after β-decay (E / TOF 5cm)	HI recoil after n-emission (E / TOF 5cm)
45	10	< 1.3 keV > 670 ns	217 keV 52 ns
	5	< 360 eV > 1.3 µs	108 keV 73 ns
	2	< 72 eV > 2.8 µs	43 keV 116 ns

This is possible because nuclei are trapped in a free environment
→ no "matrix" effects…

Beta Delayed Neutron Spectroscopy… without detecting neutrons ☺

Advantages : no need to detect neutons

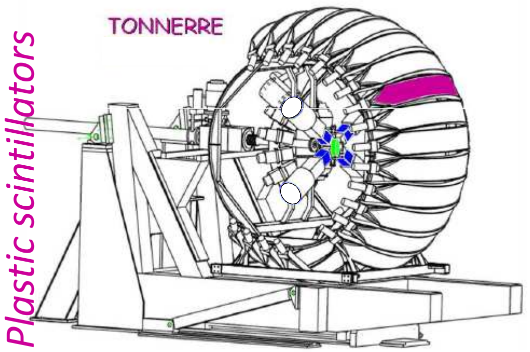
- total efficiency (β-recoil) :	up to 5%
- energy resolution (FWHM) :	~3%
- neutron energy threshold :	~30keV

- Gaussian detector response
- almost background free
- no need for γ/n discrimination

$$^{A}Z \rightarrow {}^{A}(Z+1)^{*} + \beta^{-} + \nu$$

$$\hookrightarrow {}^{A-1}(Z+1) + n$$

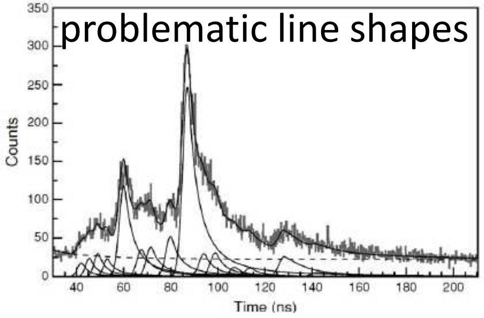
Plastic scintillators



ε_{total}(β&n) : ~15%@1 MeV

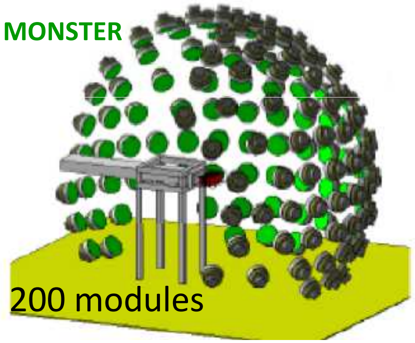
resolution : ~10%

n-threshold : ~300 keV



problematic line shapes

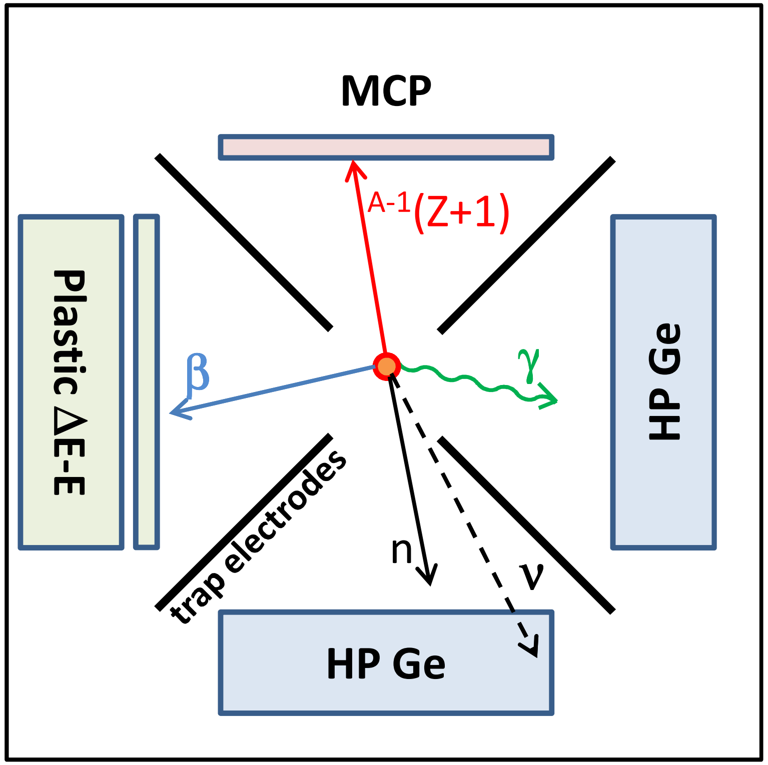
Liquid scintillators



ε_{total}(β&n) : ~5%@1 MeV

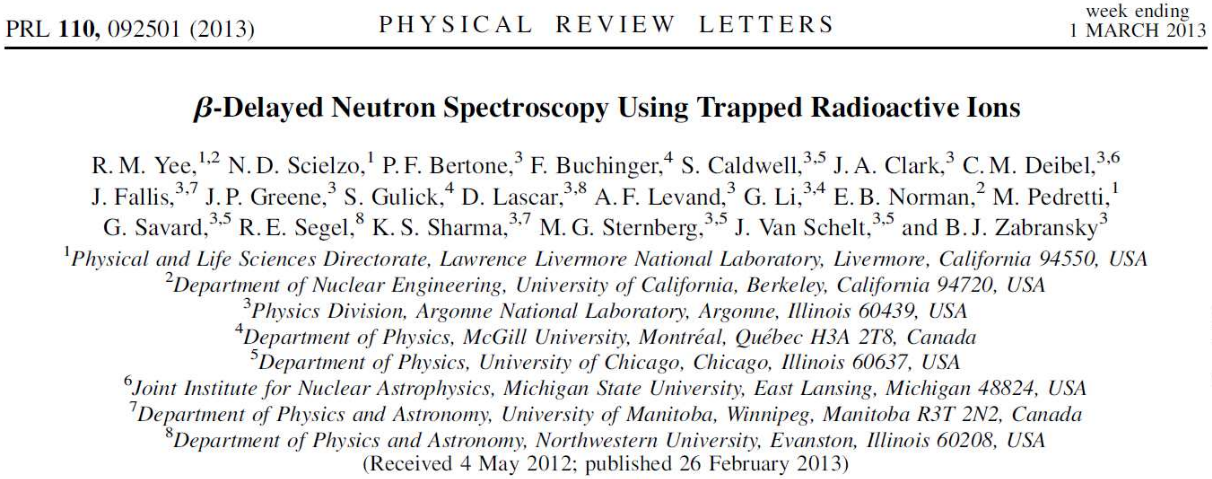
resolution : ~5%

n-threshold : ~100 keV



Seems to be a good idea…
Is it feasible ?

Proof of principle



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β-Delayed Neutron Spectroscopy Using Trapped Radioactive Ions

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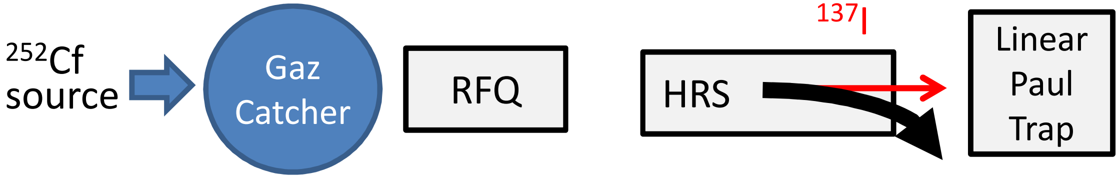

^{252}Cf source

Gaz Catcher

RFQ

HRS

137I

Linear Paul Trap

	present setup	dedicated setup
- total efficiency :	0.05 %	5%
- energy resolution	~ 10 %	3%
- n threshold	200 keV	50 keV

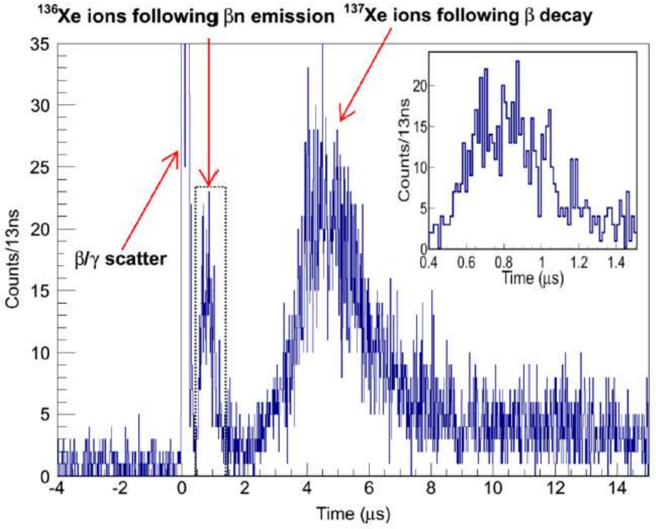

FIG. 2 (color online). Recoil-ion TOF spectrum collected with a 30 ion/s ^{137}I$^+$ beam. The TOF spectrum of the ^{136}Xe recoil ions from βn emission, highlighted by the dotted box, is shown in the inset.

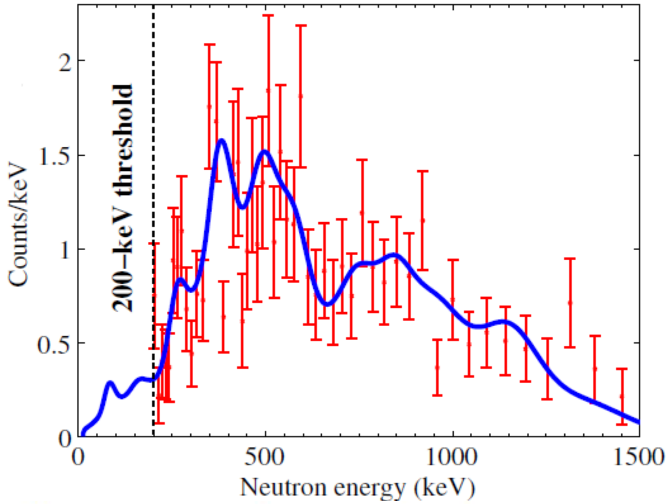

FIG. 3 (color online). Comparison of the βn-energy spectrum for ^{137}I measured here with a known spectrum from Ref. [47]

The use of Traps in Modern Nuclear Physics

Thanks for your attention

Thanks to the organizers

Thanks to K. Blaum, D. Lunney and the PIPERADE team for materials