Fundamental Studies With High-Precision Mass Measurements

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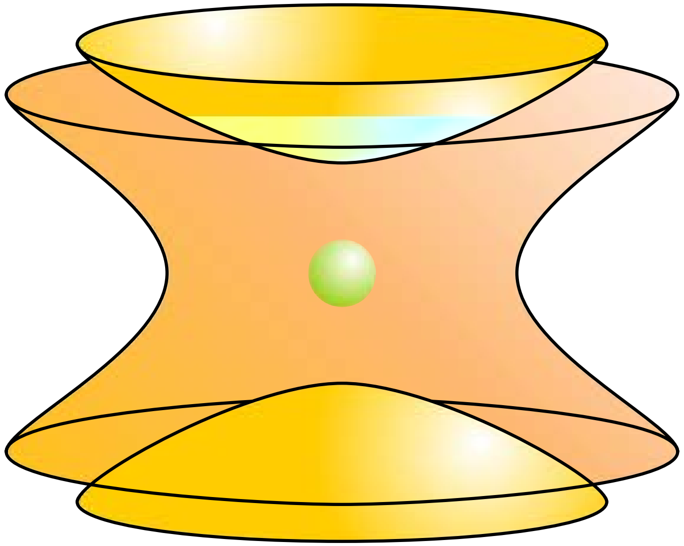
EP Seminar 2004-02-09

- Motivation
- Principle and Setup
- Recent Highlights



Mass and Energy

Energy–Mass equivalence

⇒ High-precision mass measurements convey information on binding energies

Fields of Application

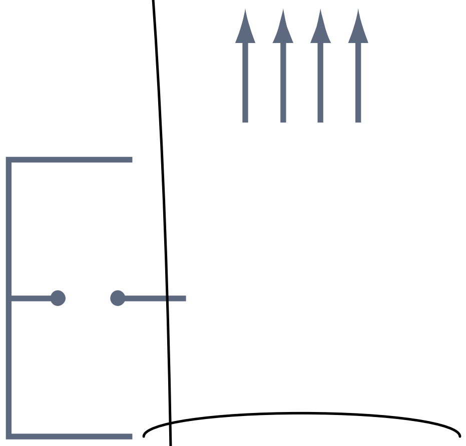
Field	Mass uncertainty
General physics and chemistry Particle identification	10^{-5}
Nuclear physics • Decay energies • Binding energies	10^{-7}
Nuclear structure • Shell closure, pairing • Deformation, halos	10^{-7}
Nuclear models and formulas • Isobaric-multiplet mass equation (IMME) • r, rp process	10^{-7}–10^{-8}
Fundamental studies • Symmetry tests • Weak interaction studies (CVC hypothesis)	10^{-8}

The Pe

Motion of a charged particle

Penning trap:

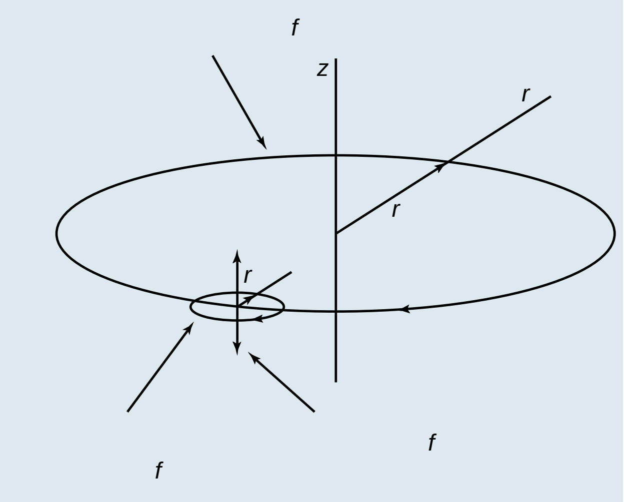
- Strong homogeneous magne
- Weak electric 3D quadrupole

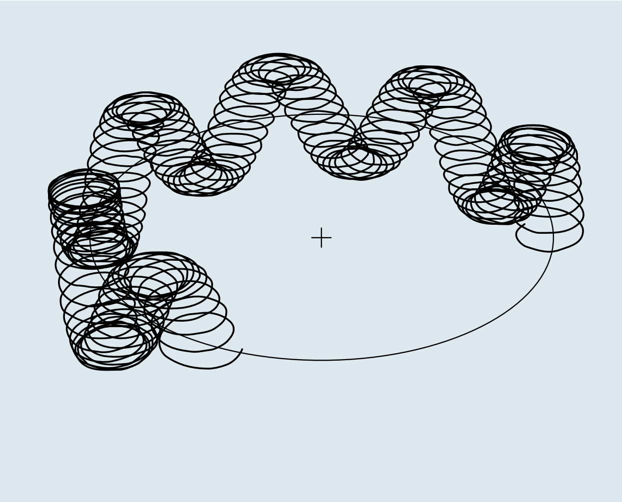


Ion Motion in a Penning Trap

Superposition of three characteristic harmonic motions:

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





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

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

The frequencies of the radial motions obey the relation

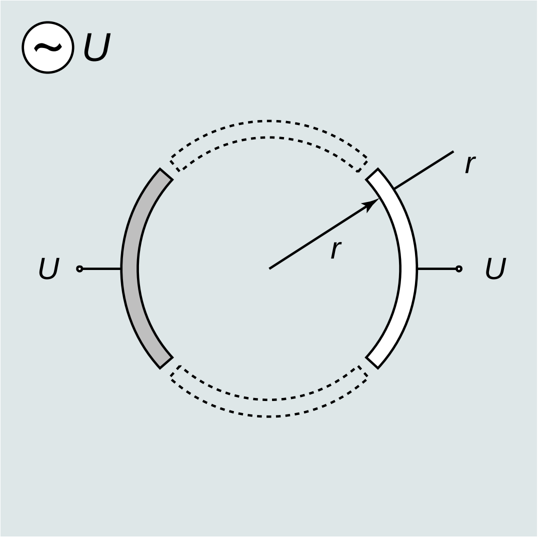
$$f_+ + f_- = f_c$$

Excitation of Radial Ion Motions

Dipolar azimuthal excitation

Either of the ion's radial motions can be excited by use of an electric dipole field in resonance with the motion (RF excitation)

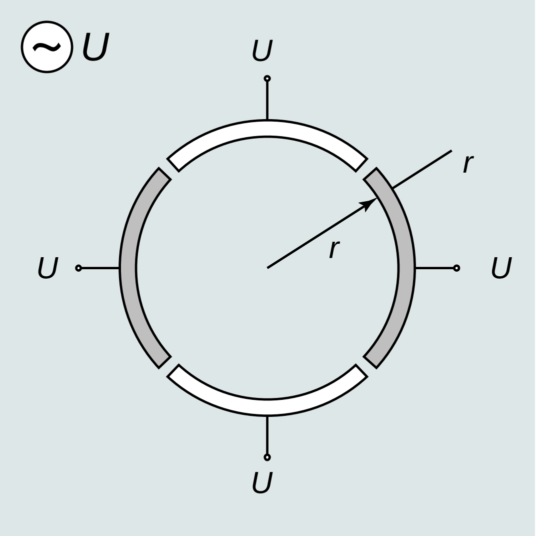
⇒ amplitude of motion increases without bounds



Quadrupolar azimuthal excitation

If the two radial motions are excited at their sum frequency, they are coupled

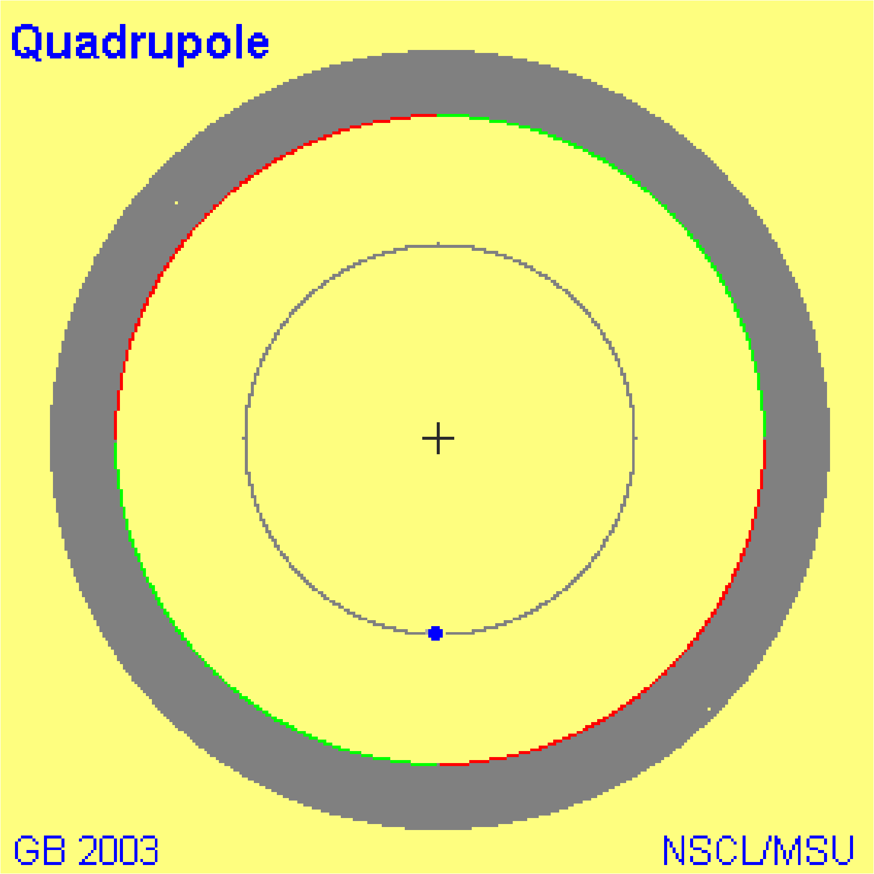
⇒ they are continuously converted into each other



Resolving power: $R = f_{\text{exc}}\, T_{\text{exc}}$

Conversion of radial motions

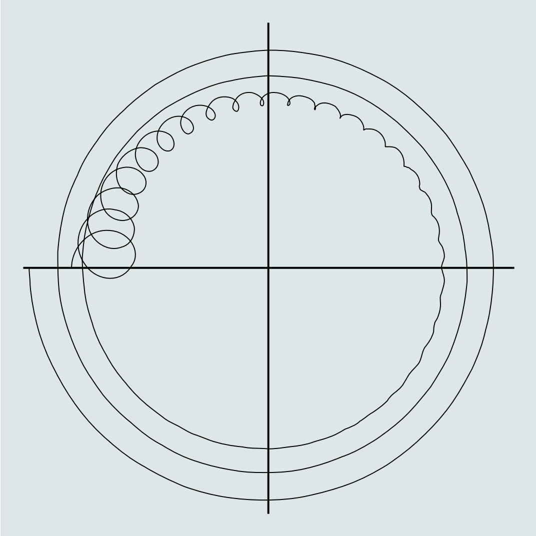
(animation)



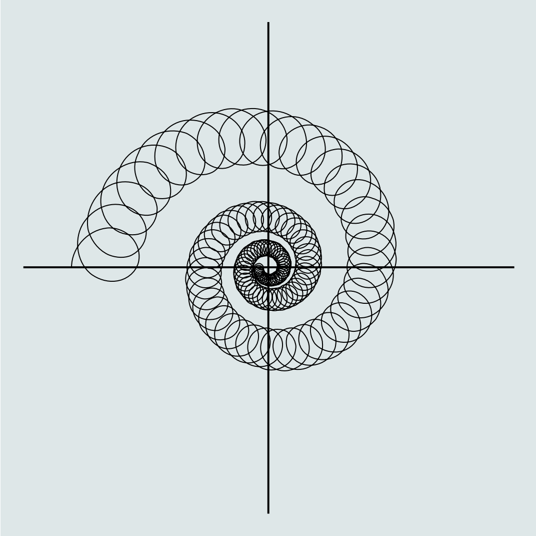
Sideband Cooling

Ion motion in the presence of cooling

- Damping of the modified cyclotron motion leads to a *decreased* cyclotron radius r_+
- Damping of the magnetron motion leads to an *increased* magnetron radius r_-



- Coupling of the motions by azimuthal quadrupolar excitation at f_c
  ⇒ radii of both motions decrease exponentially



⇒ Mass-selective cooling

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

TOF Resonance Mass Spectrometry

Time-of-flight resonance technique:

1. Dipolar radial excitation at magn. frequency f_-
   ⇒ increase of the magnetron radius r_-
2. Quadrupolar radial excitation near f_c
   ⇒ coupling of radial motions, conversion
3. Ejection along the magnetic field lines:
   Linear acceleration in inhomog. magnetic field
   ⇒ TOF to detector is reduced

Scan of excitation frequency

⇒ TOF resonance

Calibration of the magnetic field

Measurement of cyclotron frequency of a well-known nuclide (“reference mass”)

Primary result: Frequency ratio

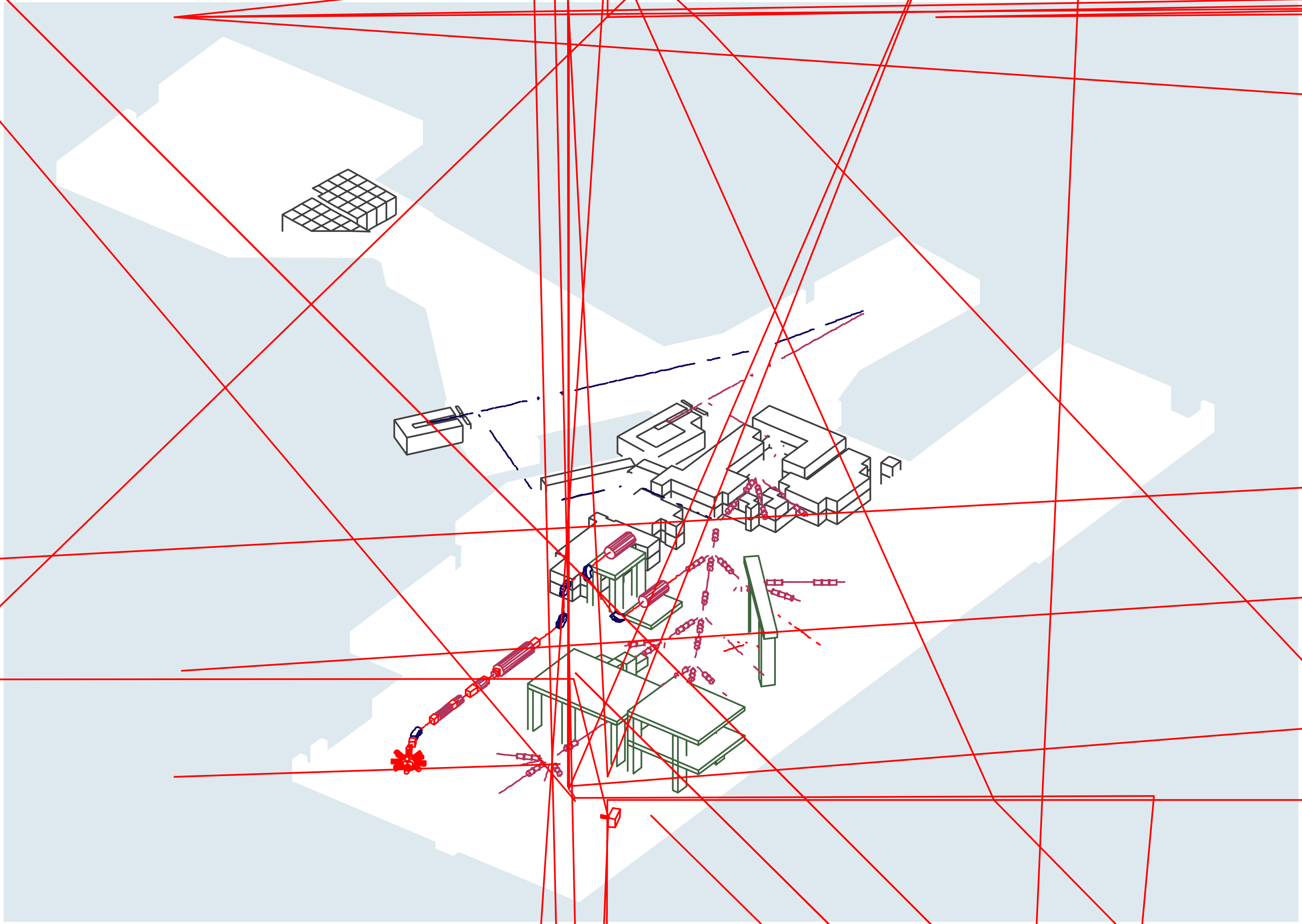
$$\frac{f_{c,ref}}{f_c} = \frac{m^+}{m^+_{ref}}$$

Reference masses: ^{23}Na ^{39}K ^{85}Rb ^{133}Cs

Masses of ^{23}Na, ^{85}Rb, ^{133}Cs known to better than 2×10^{-10}

[M. P. Bradley et al., PRL 83 (1999) 4510]

ISOLDE Experimental Hall



[illegible] dionuclides

ISOLDE Target

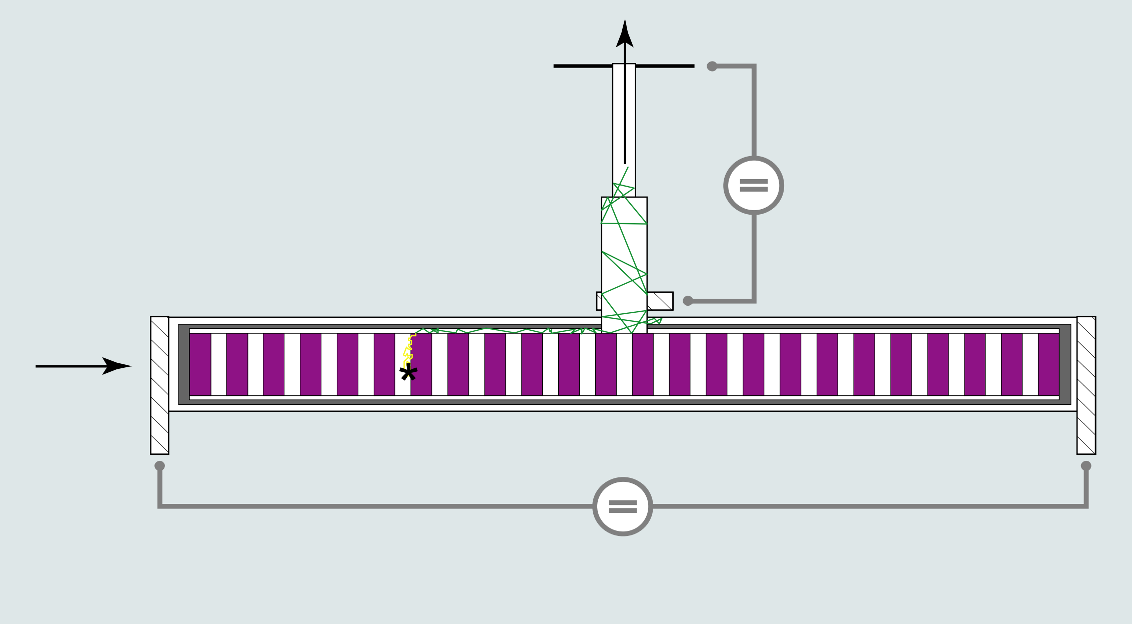
Target materials:

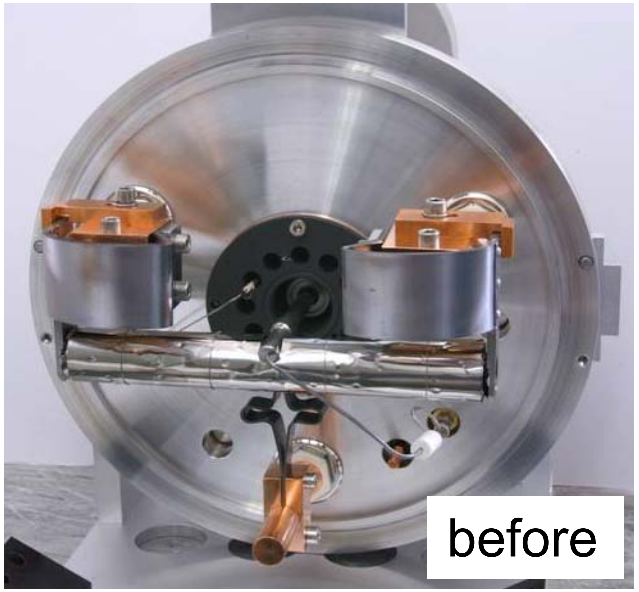
- Molten metals
- Metal powder
- Solid metals
- Carbides

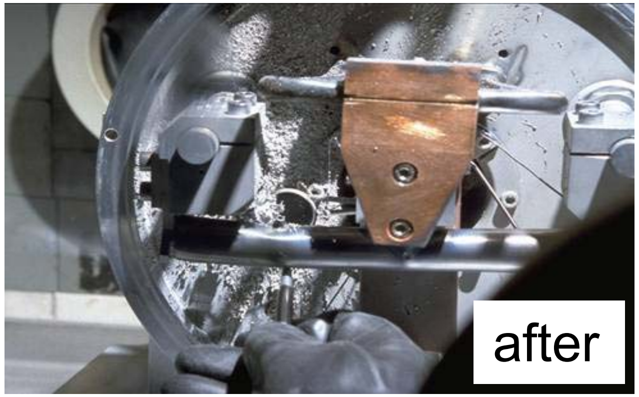
Ionization techniques:

- Surface ionization
- Plasma ionization
- Resonant laser ionization

⇒ Target–ion source combination ideally produces elementally pure ion beam




before


after

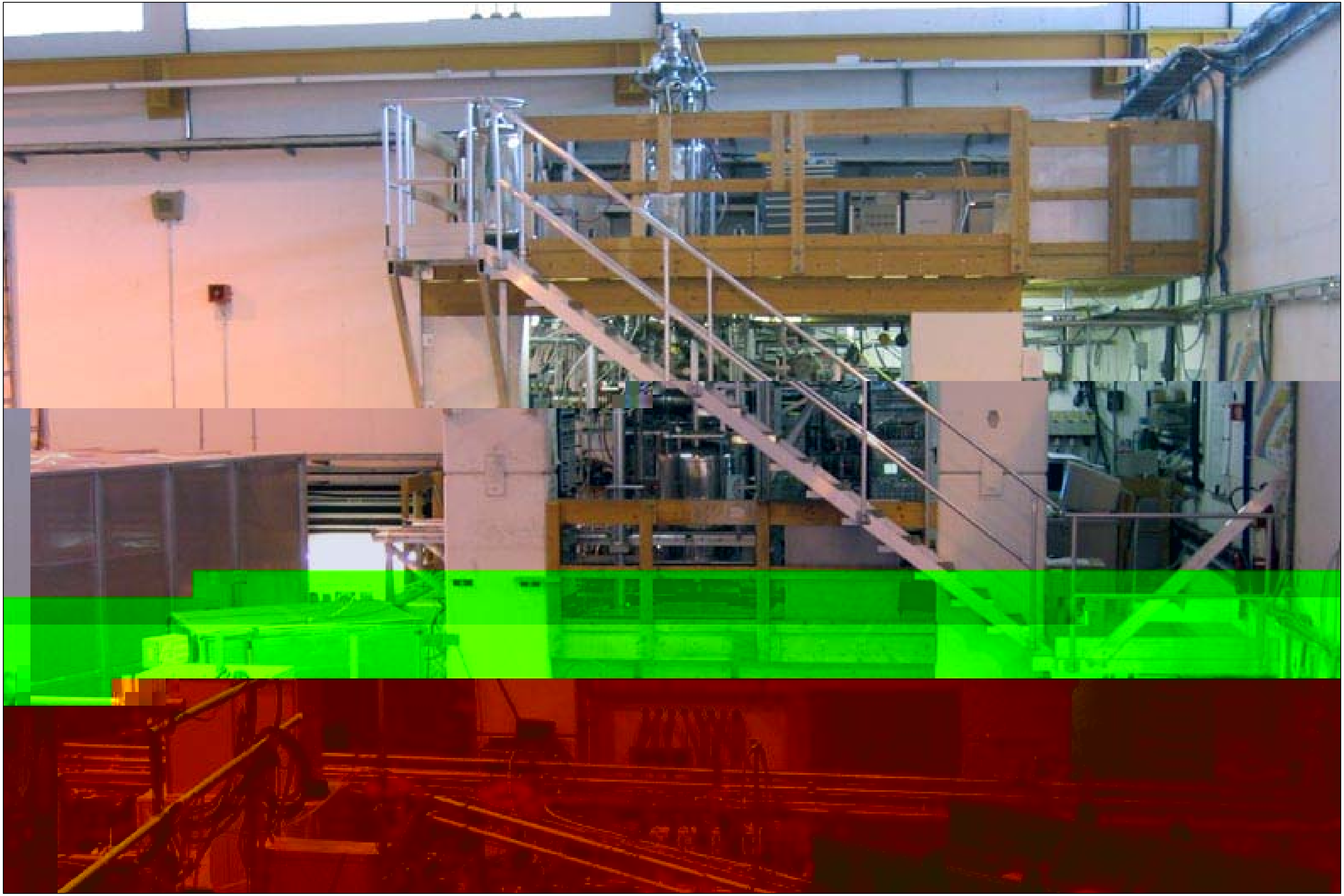
ISOLTRAP Setup

Beam preparation trap

- function: deceleration, cooling, and bunching of the ISOLDE ion beam
- linear Paul trap (RFQ ion guide)

Cooling trap

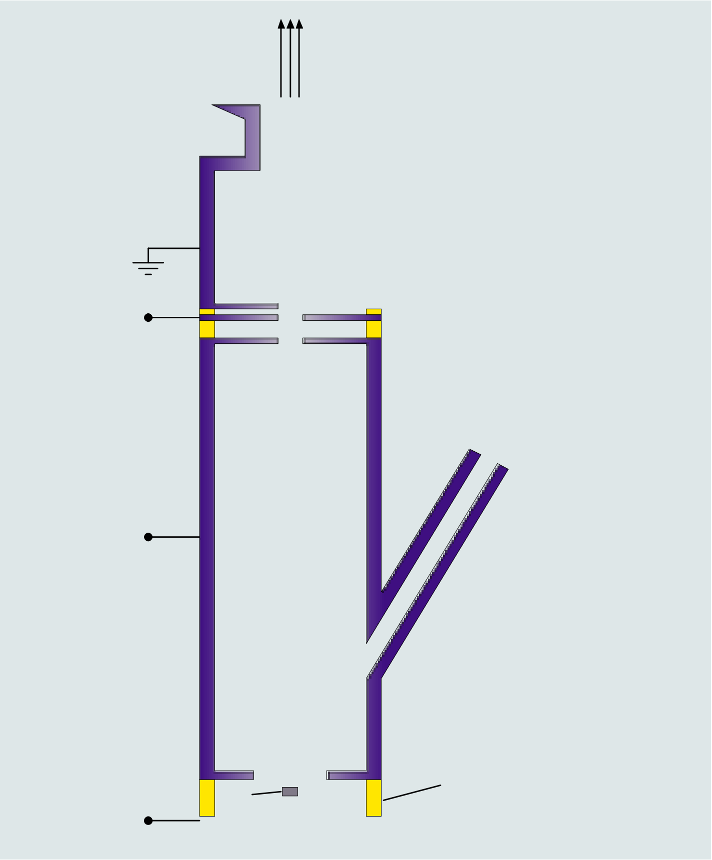
- function: mass-selective cooling
- cylindrical Penning trap in 4.7-T field
- typical resolving power: p d ☐ 0



Carbon Cluster Ion Source

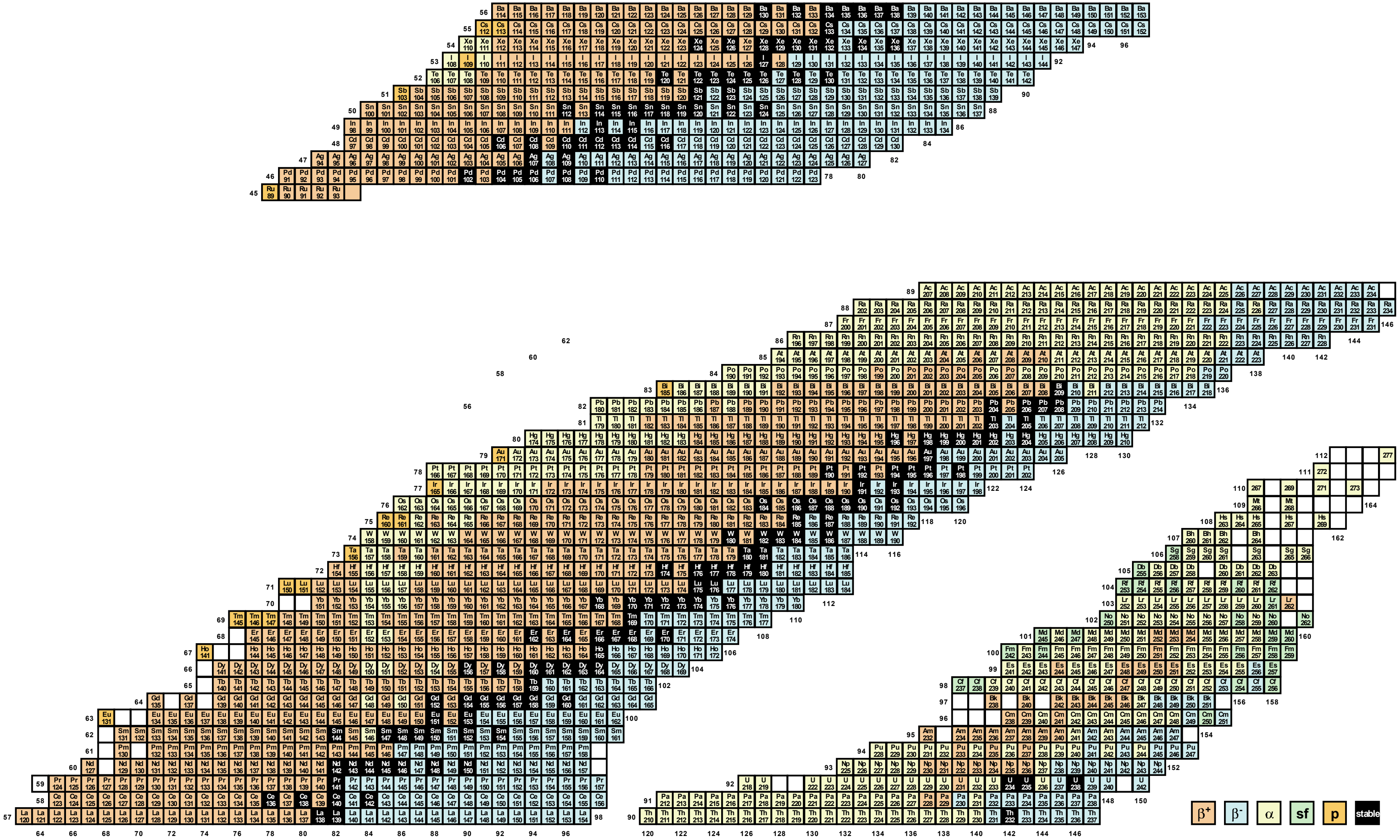
Carbon cluster production

- desorption, fragmentation, and ionization from a C_{60} pellet induced by 6-ns, 5-mJ laser pulses at 532 nm
- electrostatic acceleration to 2.7 keV and transfer to cooling Penning trap



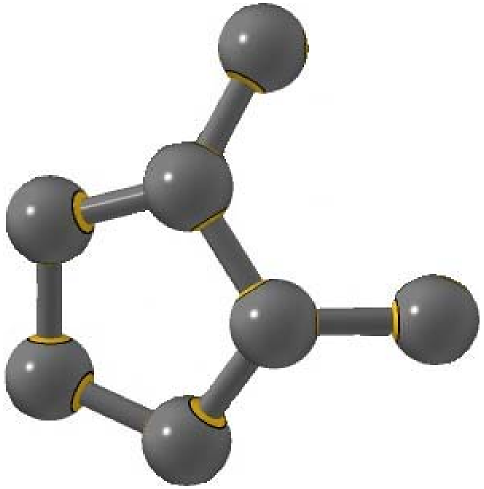
Time-of-flight spectra:

(after cooling Penning trap)


β+
β-
α
sf
p
stable

Benefits of carbon clusters as reference masses

- References throughout the chart of the nuclides
- Reference mass at most 6 u from the measured mass
- Absolute mass measurement
  (^{12}C is microscopic mass standard)
- Determination of systematic uncertainties of setup and procedure
  (mass ratios exactly known)



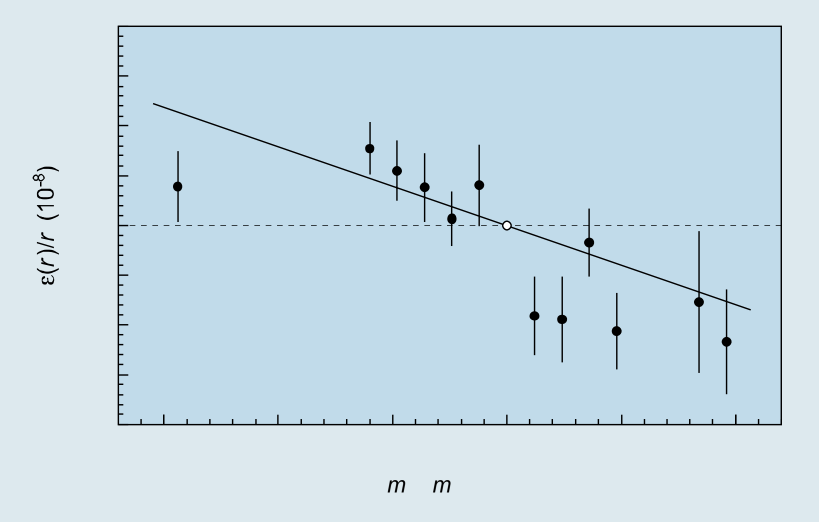
Accuracy of ISOLTRAP

Cross-reference measurements:

- Carbon clusters as both ion of interest and reference ion
- Compare actual with expected mass ratio

Mass-dependent systematic effect:

deviations of all 114 cross-reference measurements from true value

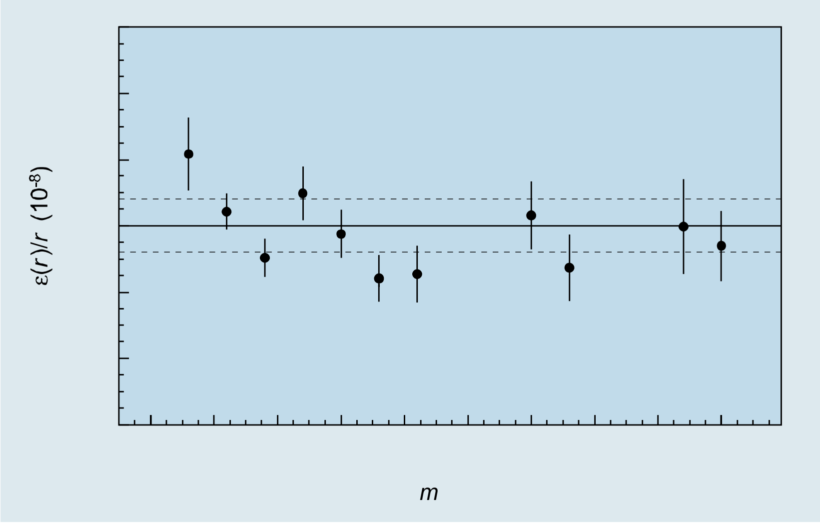


⇒ Uncertainty prop. to mass difference:

$$u_{\Delta m}(m)/m = (1.6\times10^{-10}/\mathrm{u})\times\Delta m$$

Residual systematic uncertainty:

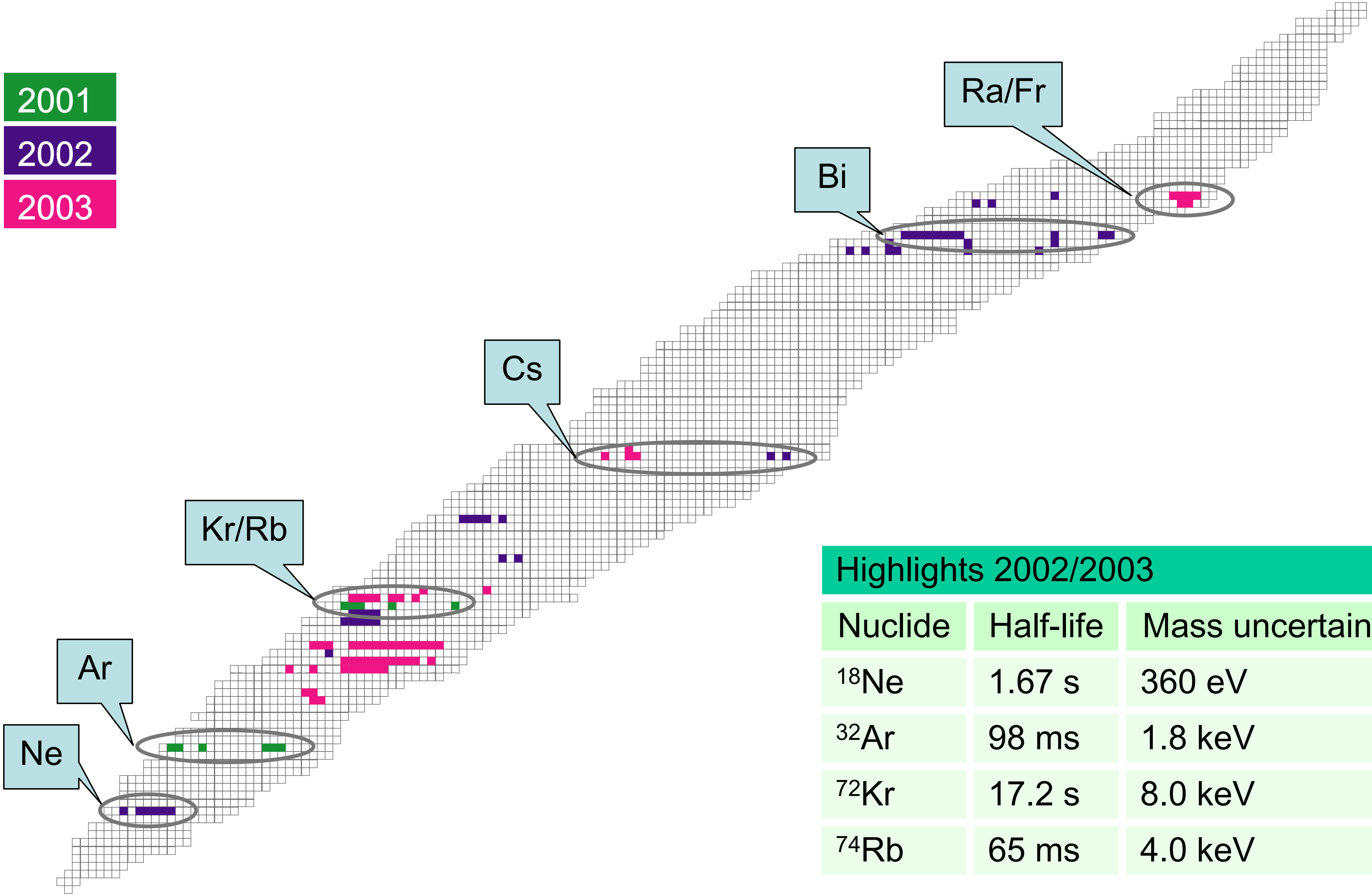
after correction for mass-dependent effect



⇒ Residual mass uncertainty:

$$u_{\mathrm{res}}(m)/m = 8.0\times10^{-9}$$

Recent ISOLTRAP Measurements



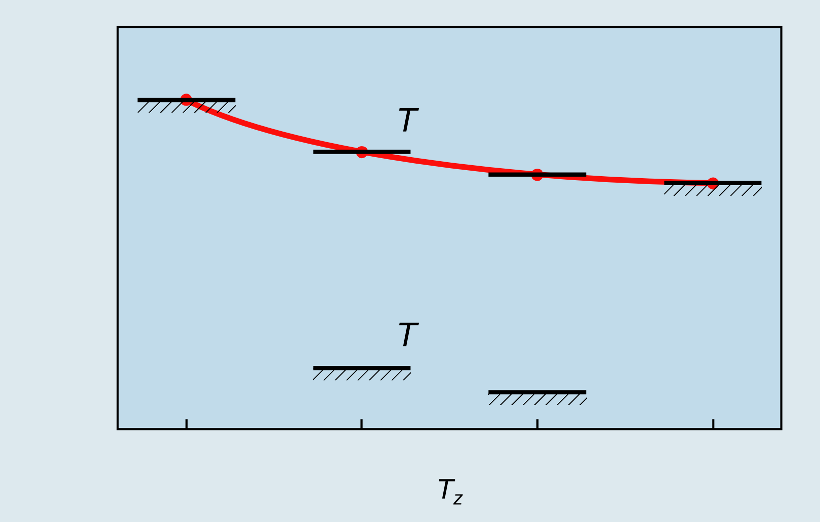
Highlights 2002/2003		
Nuclide	Half-life	Mass uncertainty
^{18}Ne	1.67 s	360 eV
^{32}Ar	98 ms	1.8 keV
^{72}Kr	17.2 s	8.0 keV
^{74}Rb	65 ms	4.0 keV

Isobaric-Multiplet Mass Equation

Mass formula for multiplets of nuclear states with same mass and isospin:

$$M = a + bT_z + cT_z^2 + dT_z^3$$

$A = 33$, $T = 3/2$ quartet:



☒ ISOLTRAP measurement on ^{33}Ar with $u(m) = 4.2$ keV:

$d = -2.95(90)$ keV

[F. Herfurth *et al.*, PRL 87 (2001) 142501]

☑ Solution: Excitation energy of $T = 3/2$ state in ^{33}Cl wrong

[M. C. Pyle *et al.*, PRL 88 (2002) 122501]

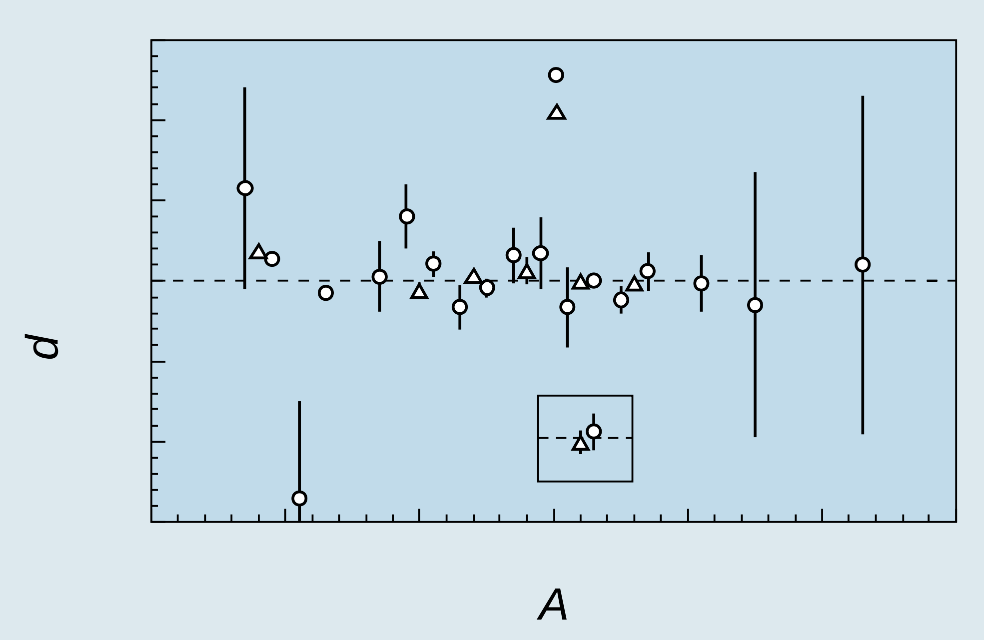
ISOLTRAP measurements 2002:

- ^{33}Ar with $u(m) = 0.44$ keV
- ^{32}Ar with $u(m) = 1.8$ keV

New status:

$A = 33$, $T = 3/2$ quartet: $d = 0.13(45)$ keV

$A = 32$, $T = 2$ quintet: $d = -0.11(30)$ keV



[K. Blaum *et al.*, PRL 91 (2003) 260801]

Superallowed β decay and the Standard Model

Conserved-vector-current hypothesis:

- Vector part of weak interaction not influenced by strong interaction
- Intensity of superallowed β decays (ft value) is only a function of the vector coupling constant and the matrix element:

$$ft = \frac{K}{G_V^2 \langle M_V \rangle^2}$$

K – Product of fundamental constants
G_V – Vector coupling constant
$\langle M_V \rangle$ – Nuclear matrix element

Corrections:

- to the nuclear matrix element $\langle M_V \rangle$:
  δ_R – radiative correction (bremsstrahlung etc.)
- to the statistical rate function f:
  δ_C – isospin symmetry breaking correction (Coulomb force, strong force)

$\Rightarrow$ Ft value constant (same numerical value for all decay pairs)

Experimental access to *Ft* value:

$$Ft = Ft\left(Q^5, T_{1/2}, b, P_{\mathrm{EC}}, \delta_{\mathrm{R}}, \delta_C\right)$$

Q – Decay energy
$T_{1/2}$ – Half-life
b – Branching ratio
P_{EC} – Electron capture fraction
δ_{R} – Radiative correction
δ_{C} – Isospin symmetry breaking correction

Unitarity of the CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \quad \begin{pmatrix} V & V & V \\ V & V & V \\ V & V & V \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{\mathrm{ud}}^2 = \frac{G_{\mathrm{V}}^2}{G_{\mathrm{A}}^2}$$

- Mean *Ft* value of all decay pairs contributes to V_{ud} via G_{V}
- Can check unitarity via sum of squares of elements of the first row

Previous status – CKM matrix

Check unitarity via elements of the first row:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \mathit{\Delta}$$

V_{us} and V_{ub} from particle physics data (*K* and *B* meson decays)

- From nuclear β decay (world average 2003):

V_{ud} obtained from avg. $\mathcal{F}t$ and G_A from muon decay

$\mathit{\Delta} = -0.0032(14)$ [I.S. Towner & J.C. Hardy, J. Phys. G 29 (2003) 197]

- From neutron decay:

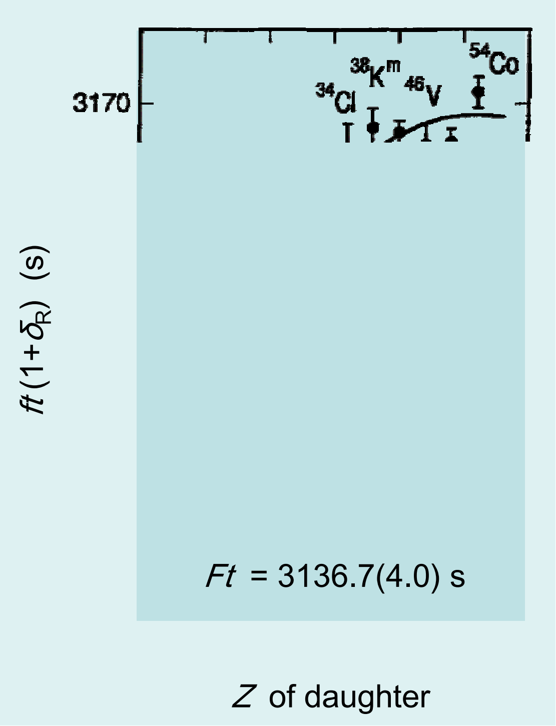
V_{ud} obtained from neutron β decay asymmetry A and lifetime τ

$\mathit{\Delta} = -0.0043(27)$ (RPP world average 2002)

$\mathit{\Delta} = -0.0083(28)$ [H. Abele *et al.*, PRL 88 (2002) 211801]

Alternative derivation of the δ_C parameter

- Assume that $\delta_C = 0$ for $Z_f = 0$
- Extrapolate $ft\,(1+\delta_R)$ to $Z_f = 0$ with a quadratic polynomial



$\mathcal{F}t$ = 3136.7(4.0) s

New measurement of V_{us} from K_{e3}^{+} decay

$|V_{us}| = 0.2272(23)(07)(18)$

but :

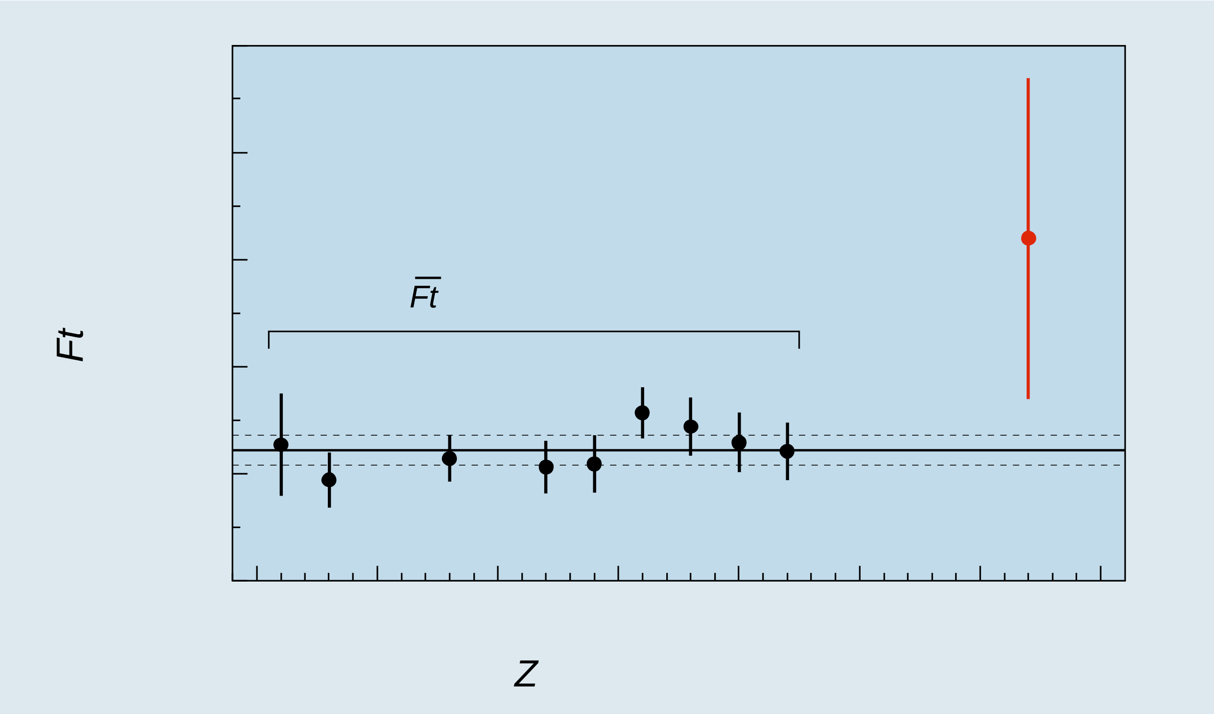
- in disagreement with previous K_{e3}^{+} decay data
- in disagreement with K_{e3}^{0} decay data

Results – *Ft* value

^{74}Kr: $T_{1/2}$ = 11.5 min $u(m)$ = 2.1 keV

^{74}Rb: $T_{1/2}$ = 65 ms $u(m)$ = 4.0 keV (previously 720 keV)

From ISOLTRAP data: $Ft(^{74}\text{Rb})$ = 3092(15) s



Uncertainty budget:

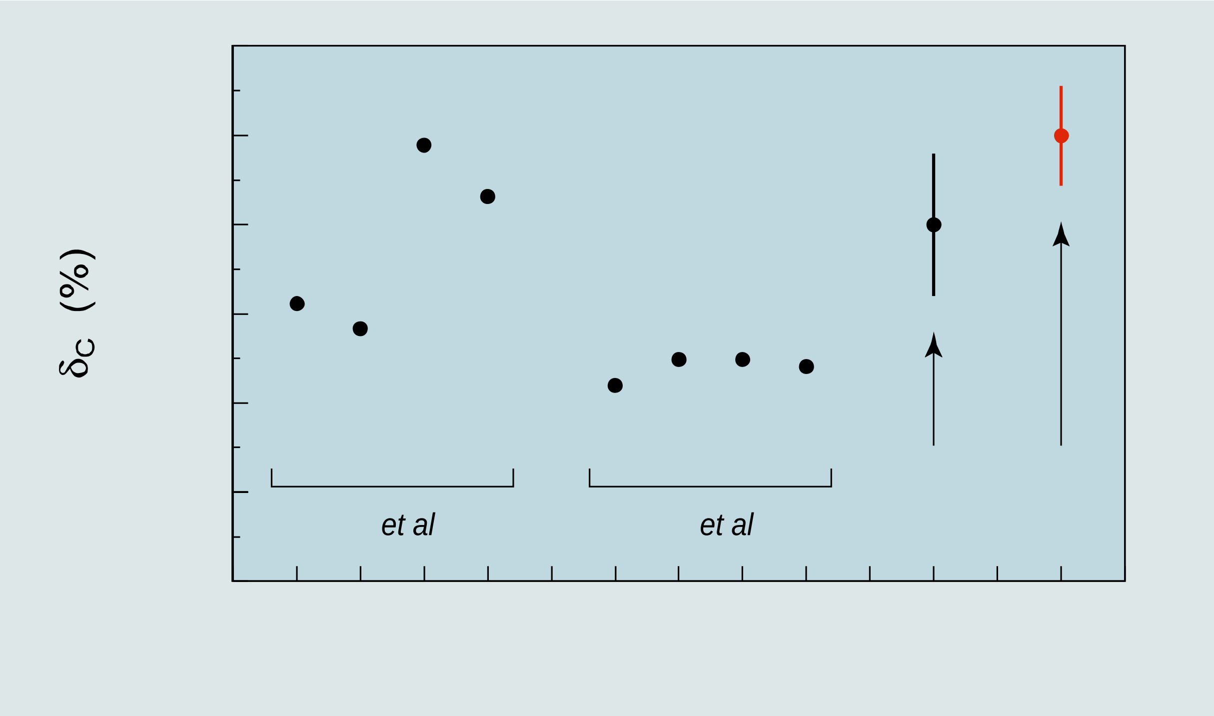
	rel. unc.	contribution
δ_C	2.7×10^{-1}	67%
Q	4.3×10^{-4}	22%
δ_R	8.0×10^{-2}	6%
R	1.0×10^{-3}	4%
$T_{1/2}$	4.5×10^{-4}	1%
P_{EC}	1.0×10^{-1}	0%

- $Ft(^{74}\text{Rb})$ in 1.3-σ disagreement with data from lighter nuclides
- Uncertainty too large for clear statement on CVC

Results – δ_C value

Assumption: Vector current is conserved

From ISOLTRAP result: $\delta_C(^{74}\text{Rb}) = 1.95(28)\%$



Uncertainty budget:

	rel. unc.	contribution
Q	4.3×10^{-4}	65%
δ_R	8.0×10^{-2}	17%
R	1.0×10^{-3}	12%
$\overline{Ft}$	4.6×10^{-4}	3%
$T_{1/2}$	4.5×10^{-4}	2%
P_{EC}	1.0×10^{-1}	0%

- Experimental δ_C larger than all proposed calculated values
- Values of Ormand *et al.* favored, especially those using Woods-Saxon single-particle wavefunctions

Conclusions and outlook

- ISOLTRAP can perform high-precision mass measurements ($< 10^{-8}$) on very short-lived nuclides (< 100 ms) that are produced with very low yields (< 100 ions/s)
- Such high-precision mass measurements can provide valuable input to fundamental studies
- Superallowed β decays:
  - Mass measurements on ^{74}Rb and ^{74}Kr have reduced the uncertainties of Q and Ft for $^{74}\mathrm{Rb}(\beta^{+})^{74}\mathrm{Kr}$ by more than two orders of magnitude
  - Uncertainty of Ft (^{74}Rb) now limited by calculated correction factors ⇒ More detailed calculations of correction factors required for clear statement on CVC hypothesis
  - Measurements on more superallowed β decays planned for 2004: ^{22}Mg, ^{26m}Al, ^{62}GaG a

The ISOLTRAP Collaboration

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and the ISOLDE collaboration