High-Accuracy Mass Measurements with SMILETRAP

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Introduction to SMILETRAP

- **Objective :** High-precision (ppb) atomic mass spectrometry using highly charged ions

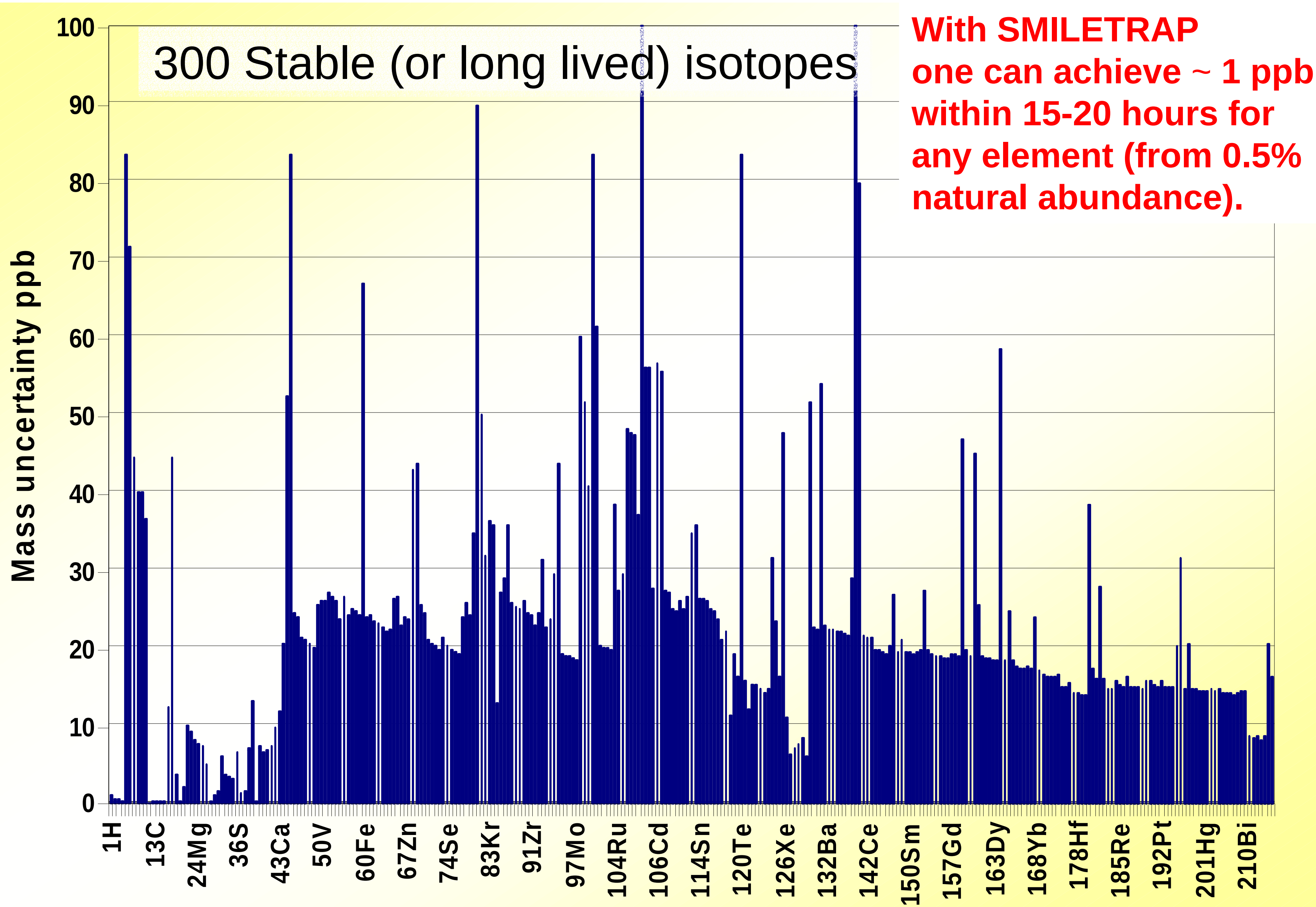
- **Principle :** Measurement of the cyclotron frequency of an ion trapped in a homogeneous magnetic field :

$$\nu_c = \frac{1}{2\pi}\frac{qeB}{m} \qquad \frac{m}{\Delta m} = \frac{\nu_c}{\Delta \nu_c}$$

➔ using HCI increases the precision linearly

- **The experiment :**
  - A CHORDIS source to produce high intensity beam of mono-isotopic singly charged ions
  - An EBIS to produce HCI,~U^{65+} (Neon like ions)
  - A PENNING trap

Current knowledge of atomic masses from most recent compilation (1997)



With SMILETRAP one can achieve ~ 1 ppb within 15-20 hours for any element (from 0.5% natural abundance).

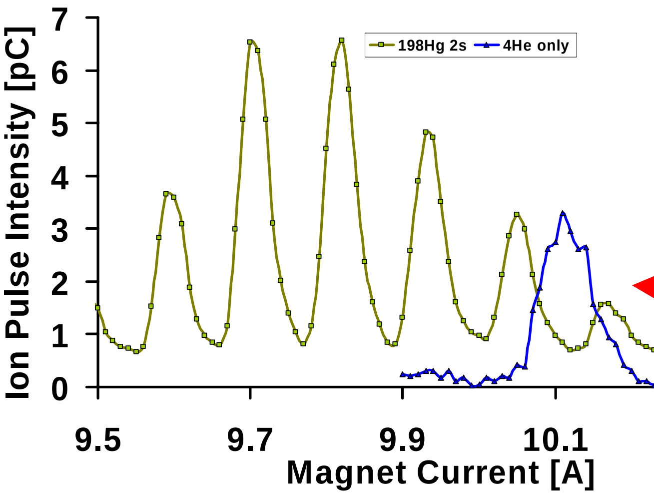
Where does the mass of an atom or ion matter?

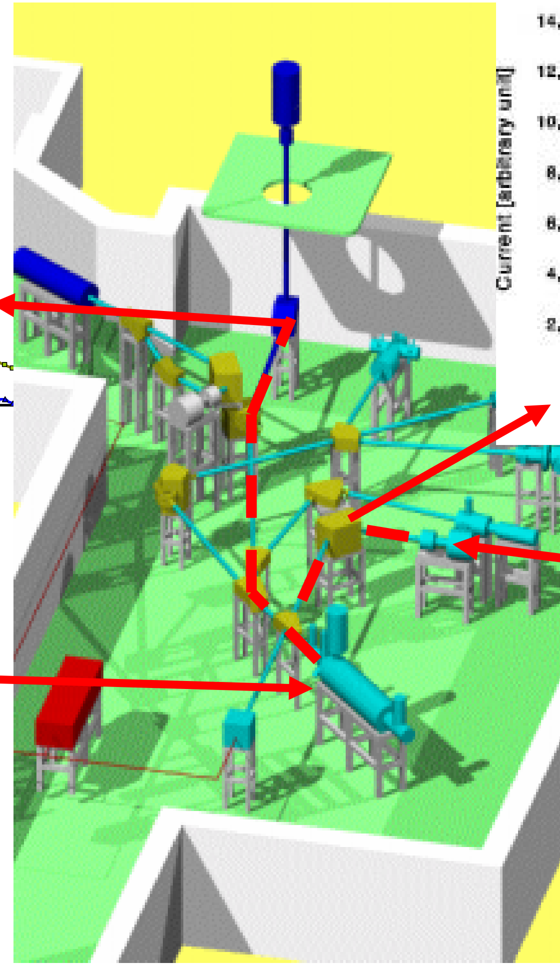
- ^{28}Si for atomically defined kilogram mass standard
- ^{76}Ge for constraints on neutrino-less double beta decay
- ^{133}Cs, for accurate determination of the fine structure constant α
- ^{24}Mg and ^{26}Mg for bound-electron *g* factor determination in hydrogen-like ions
- $^{198-204}$Hg to solve the “mercury problem” in Audi/Wapstras mass table
- Determination of the electron binding energies in heavy atoms

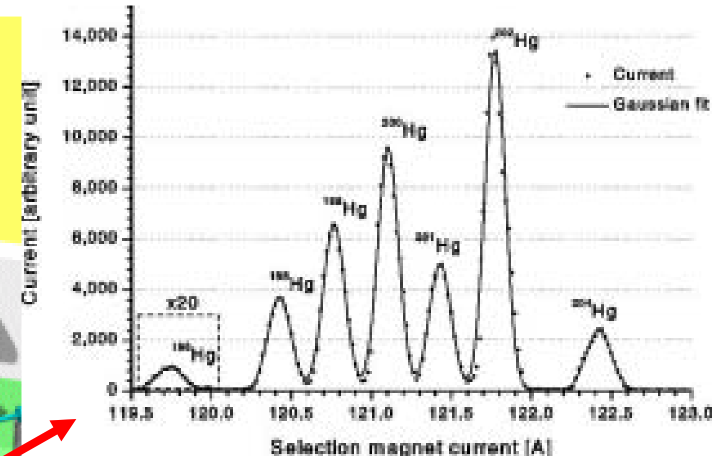
……

… a relative mass accuracy of $\Delta m/m$ = 10^{-9}-10^{-10} is required

The CHORDIS/CRYSIS ion sources:



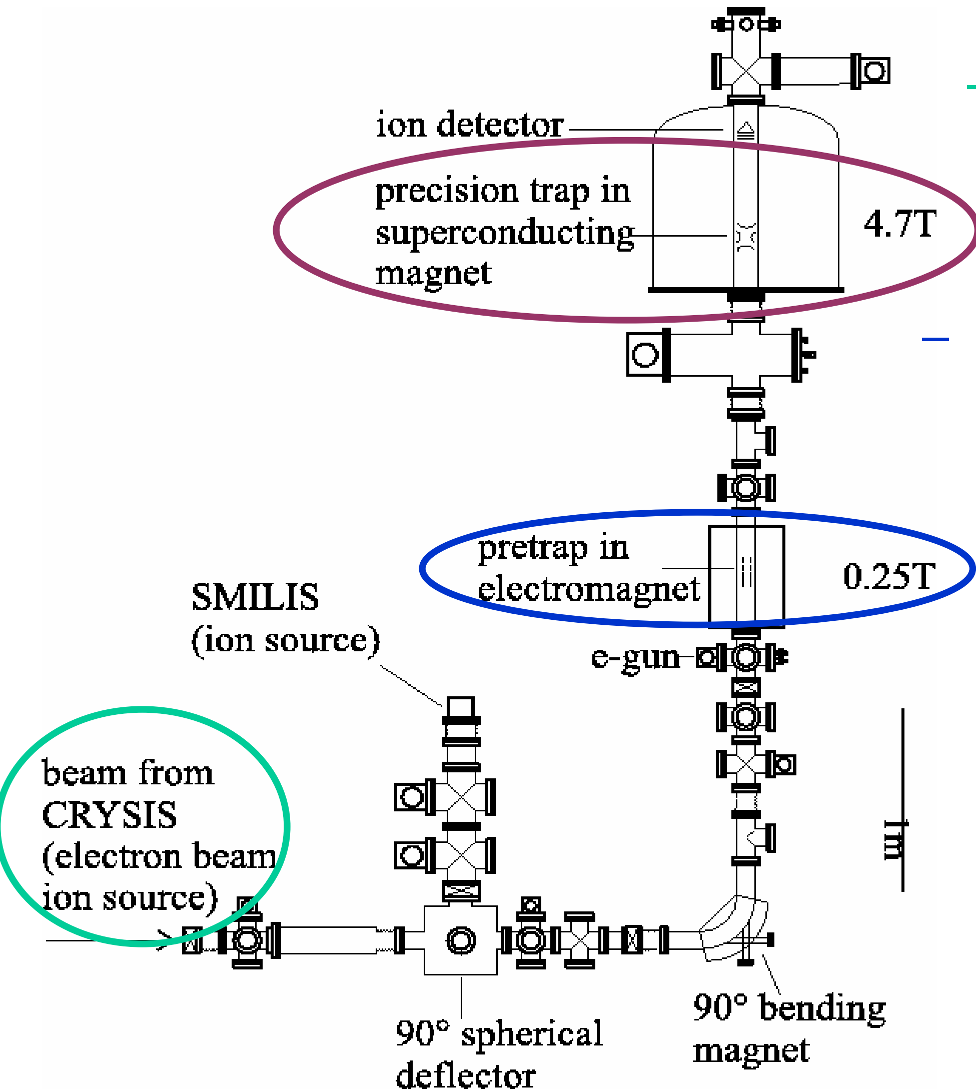




CRYSIS
Production of highly charged ions by electron bombardment

CHORDIS
Production of singly charged isotope separated ions

SMILETRAP setup and Ion budget



– *EBIS*
  - Out from CRYSIS : 10^8 Ge ions
  - 25% on Ge^{22+} : 2.5×10^7 ions
– *PreTrap*
  - After magnet and retardation : 10^6 ions
  - 1/250 beam captured : <4000
    – pretrap length/beam length
    – 2 V deep trap / 7 V energy spread
– *Precision Trap*
  - After injection aperture : 150 ions
  - Captured : 50 ions
  - After energy selection : 1-4 ions
    – 50 mV / 2 V

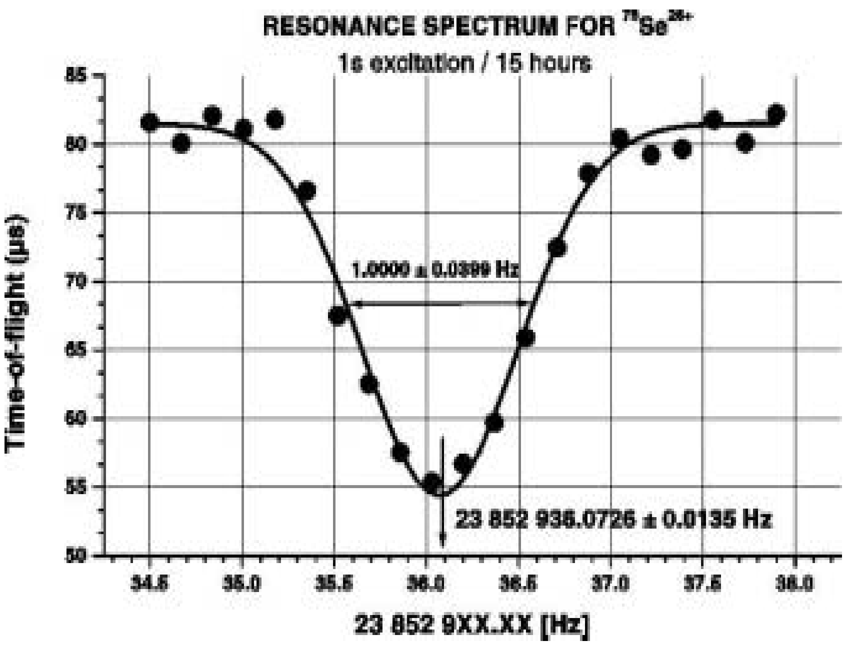
I. Bergström, et al., Nucl. Instr. Meth. A, 487 618-651 (2002).

How to determine the mass of an atom?

$$\nu_c = \frac{1}{2\pi}\frac{qeB}{m}$$

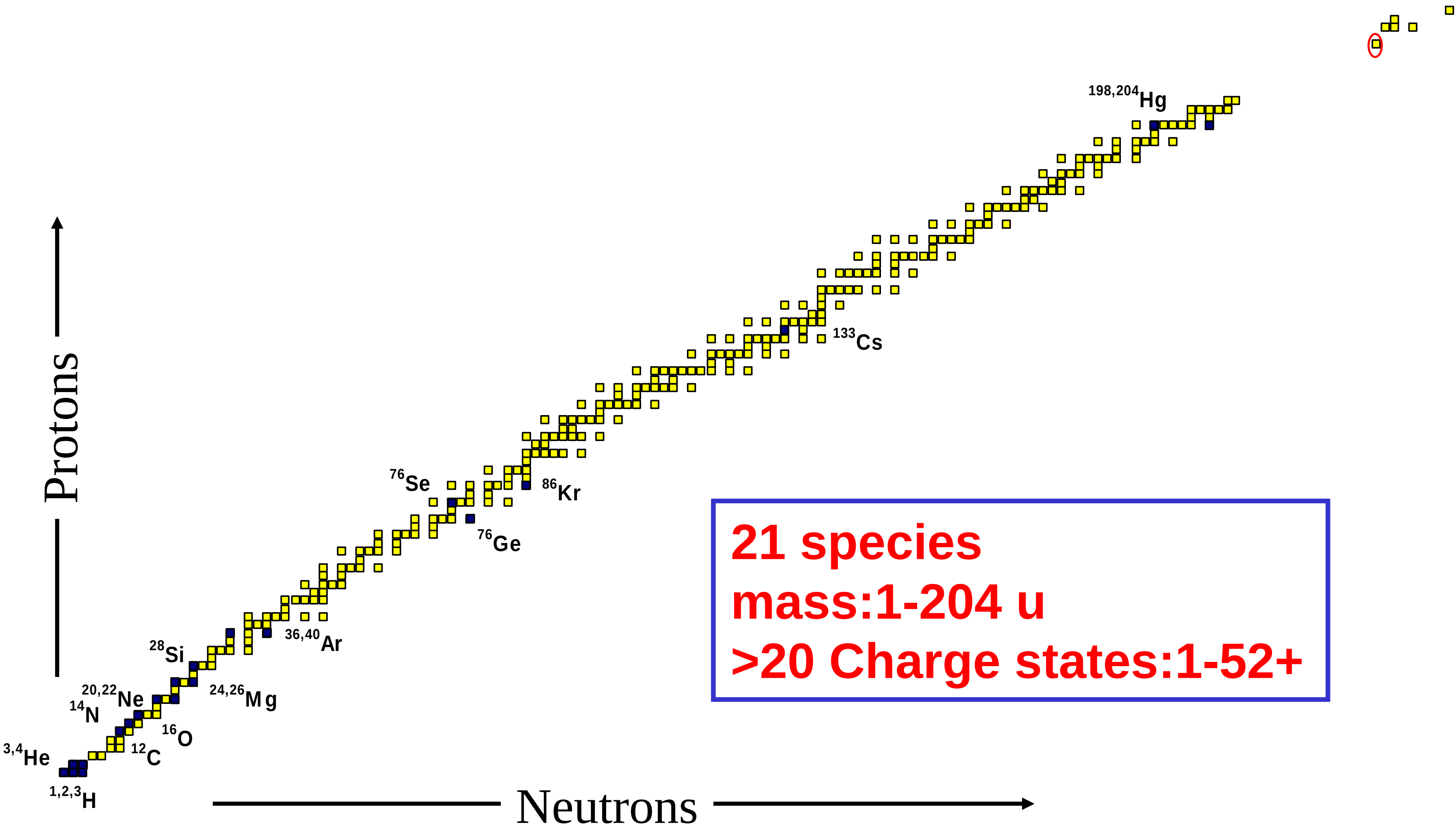
$$\Delta\nu_c[Hz] \approx \frac{1.0}{T_{exc}[s]}$$

$$\frac{m}{\Delta m} = \frac{\nu_c}{\Delta\nu_c}$$



$$R = \frac{\nu_c}{\nu_{cREF}} = \frac{q m_{REF}}{q_{REF} m} \Rightarrow M_A = \frac{1}{R}\frac{q}{q_{REF}} m_{REF} + q m_{e^-} - E_B(A^{q+})$$

Masses measured at SMILETRAP 1997-2002

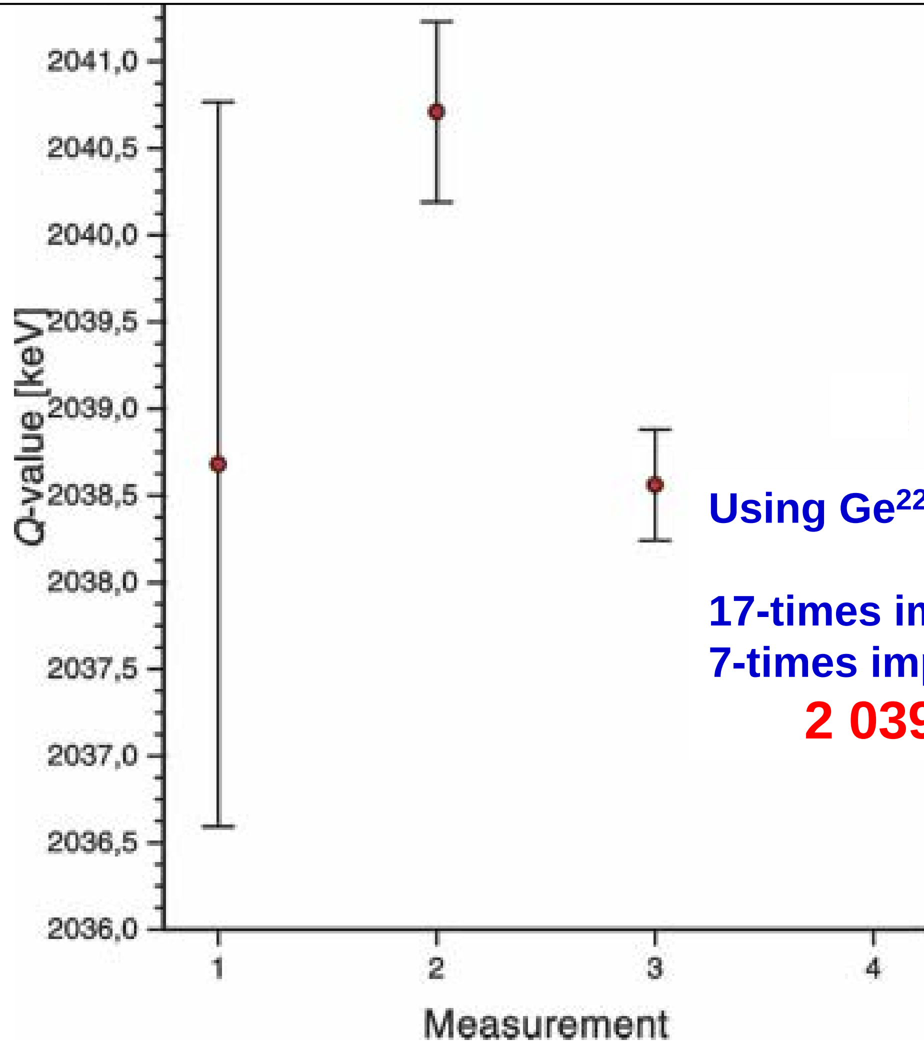


21 species
mass:1-204 u
>20 Charge states:1-52+

^{76}Ge for constraints on neutrino-less double beta decay

Question: Is there a ν-less double β-decay?

Reaction: $${}^{76}_{32}Ge \rightarrow {}^{76}_{34}Se + 2e^{-} (+2\bar{\nu}_e\ ?)$$

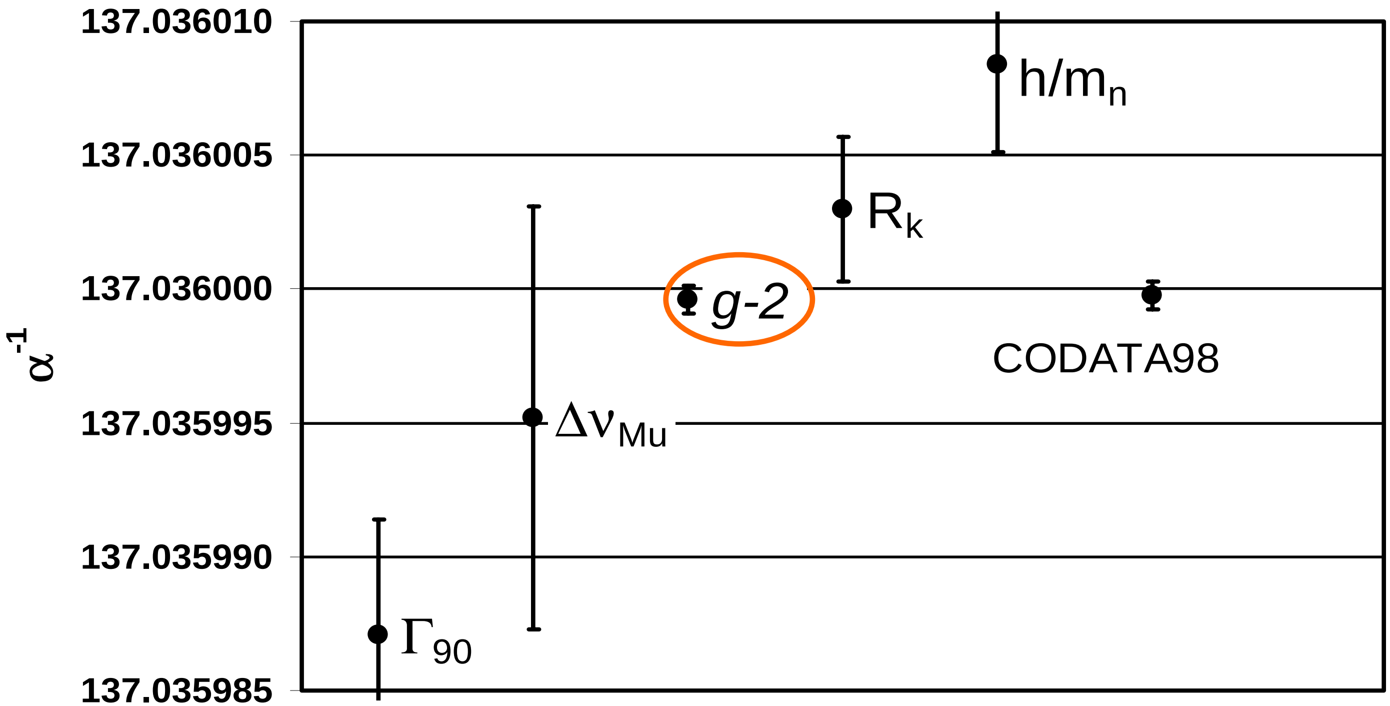


Using $Ge^{22,23+}$ and $Se^{24,25+}$ ions:

17-times improvement in both masses
7-times improvement in the *Q*-value

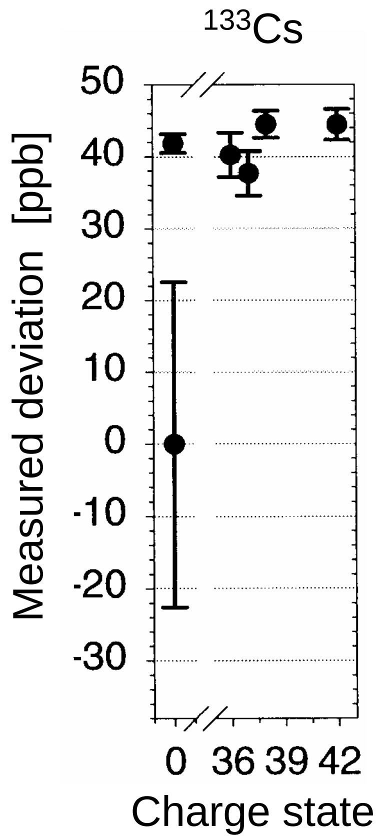
2 039.006(50) keV

Present status of the fine structure Constant α



^{133}Cs for accurate determination of the fine structure constant α

$$\alpha^2 = \left(\frac{2R_\infty}{c}\right)\left(\frac{h}{m_e}\right) = \left(\frac{2R_\infty}{c}\right)\left(\frac{h}{m_{Cs}}\right)\left(\frac{m_{Cs}}{m_p}\right)\left(\frac{m_p}{m_e}\right)$$



2 ppb (0.4ppb by M. P. Bradley et al.,)

^{133}Cs for accurate determination of the fine structure constant α

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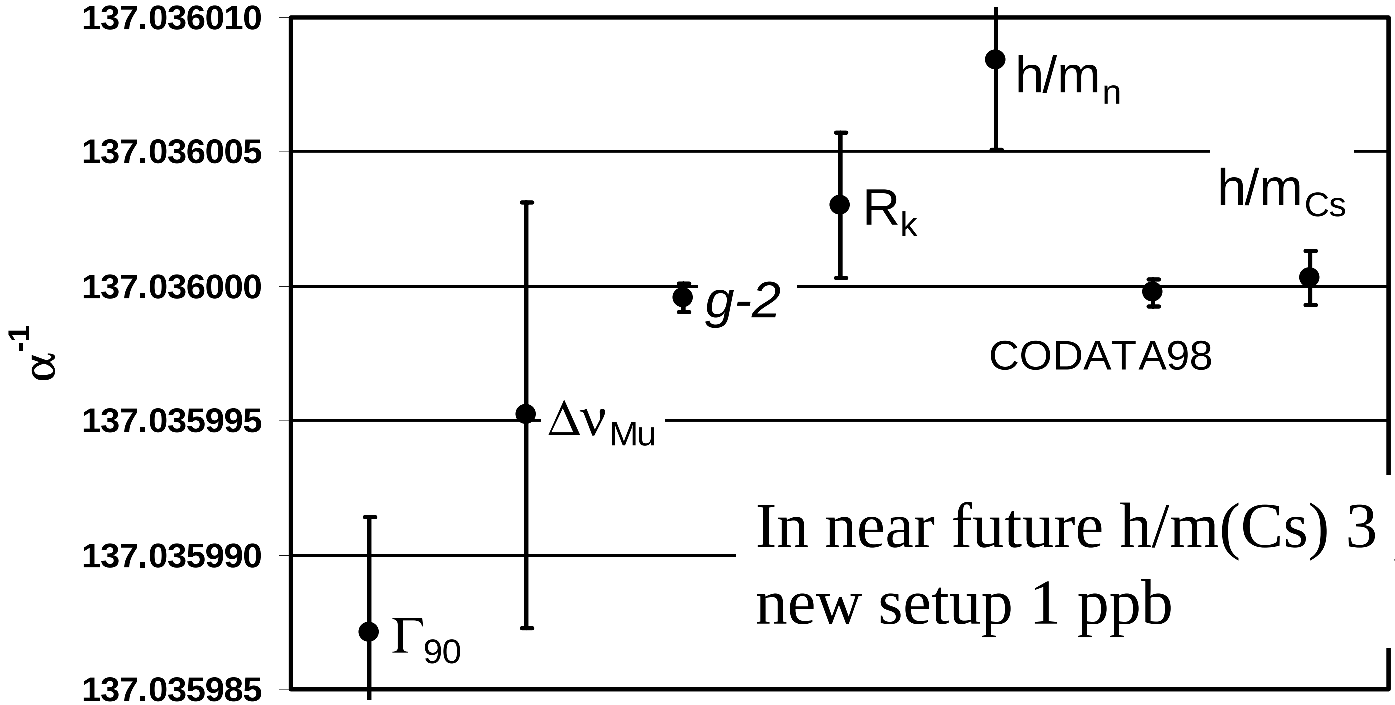
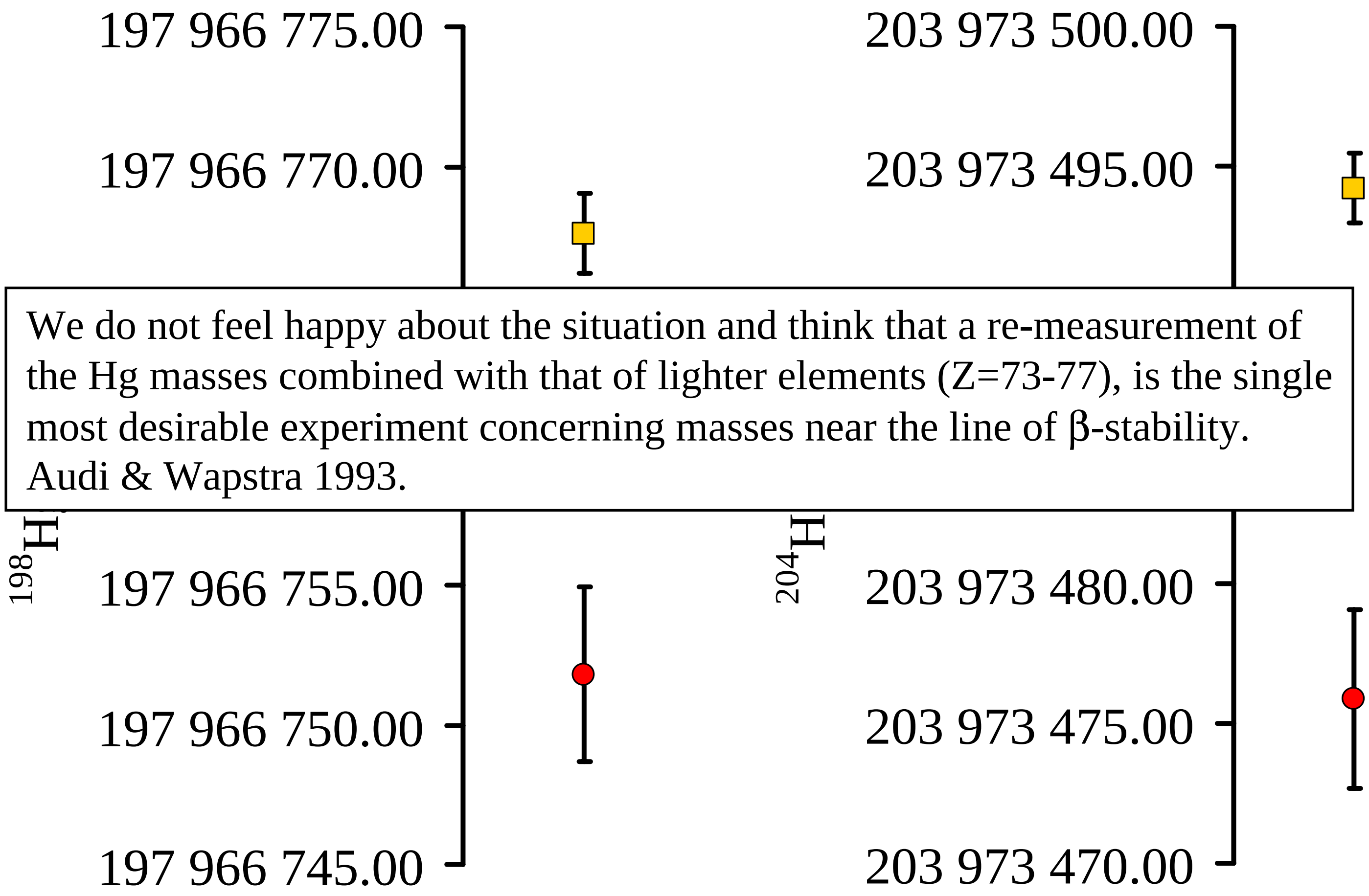
- $\frac{2R_\infty}{c}$: **$< 2\cdot10^{-11}$**
- $\frac{h}{m_{Cs}}$: **7.3 ppb**
- $\frac{m_{Cs}}{m_p}$: **2 ppb** (0.4ppb by M. P. Bradley et al.,)
- $\frac{m_p}{m_e}$: **2.2 ppb**, 0.7 ppb from g-factor, C^{5+}



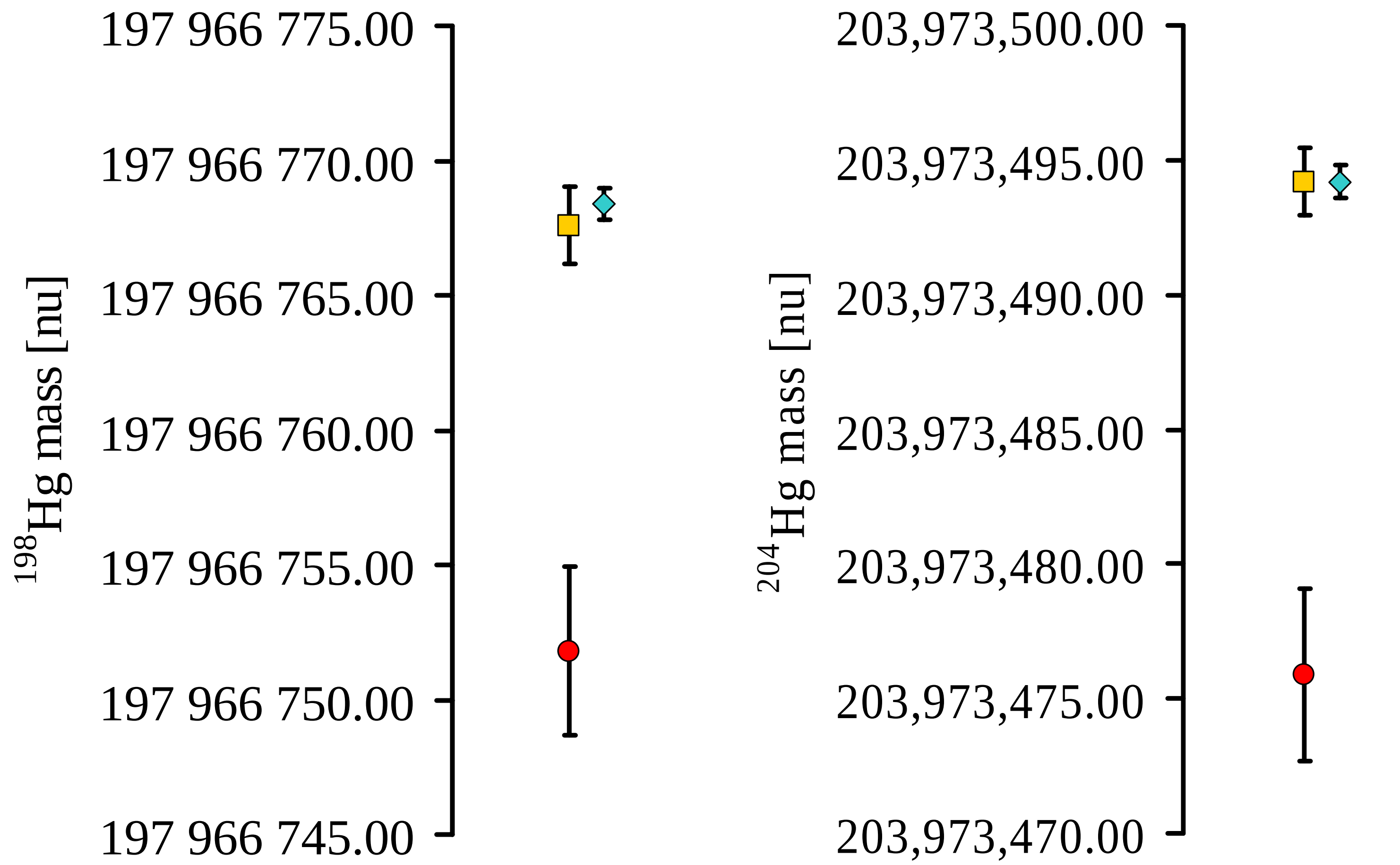
In near future h/m(Cs) 3 ppb
new setup 1 ppb

The "mercury problem" in Audi and Wapstras mass table



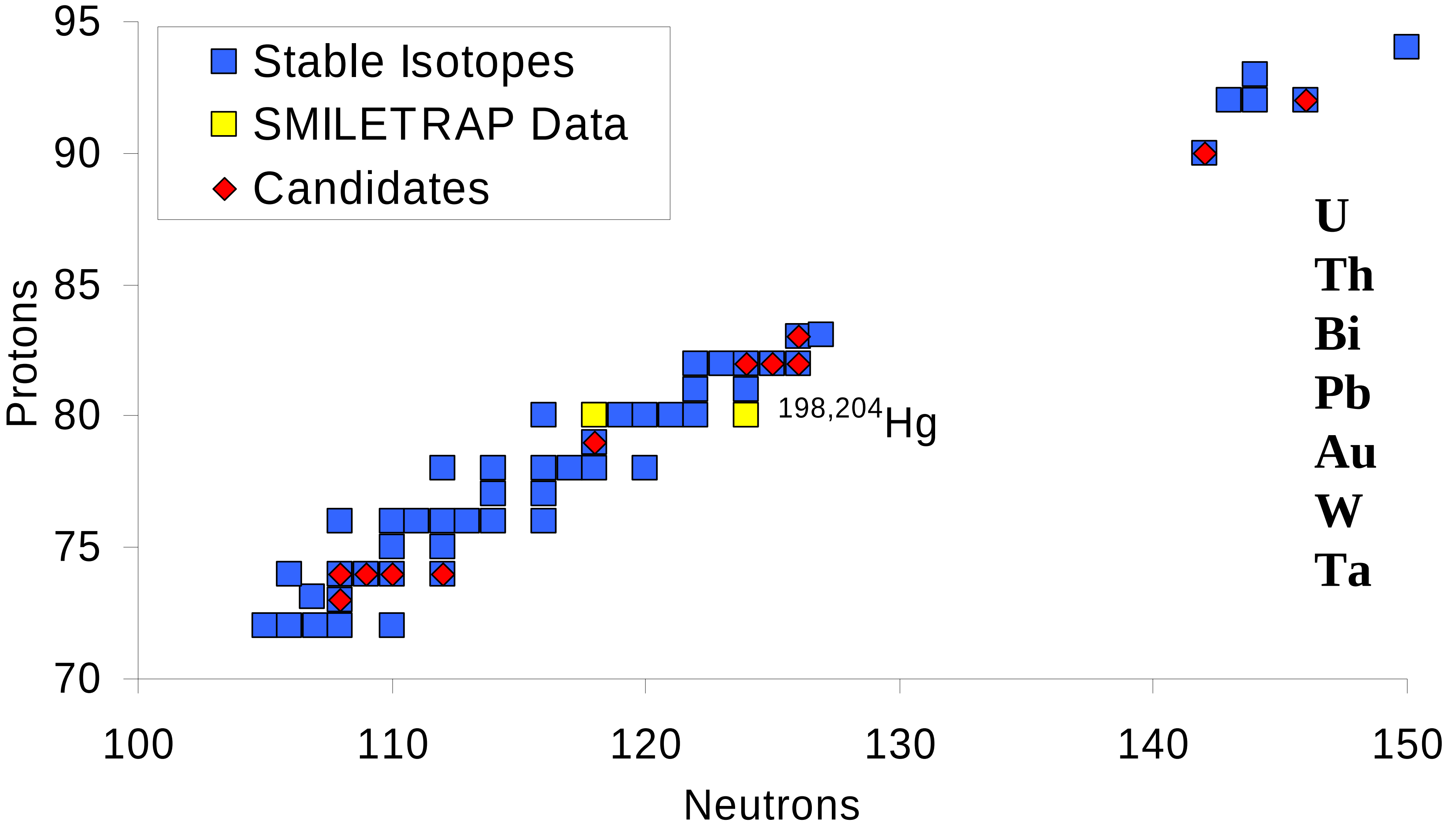
We do not feel happy about the situation and think that a re-measurement of the Hg masses combined with that of lighter elements (Z=73-77), is the single most desirable experiment concerning masses near the line of β-stability.
Audi & Wapstra 1993.

Is the “mercury problem” solved?



Manitoba results confirmed ☺ **$\Delta m/m = 2\cdot10^{-9}$**

Important candidates to solve the "mercury problem"



Determination of electron binding energies

New tests on theory?

Examples:

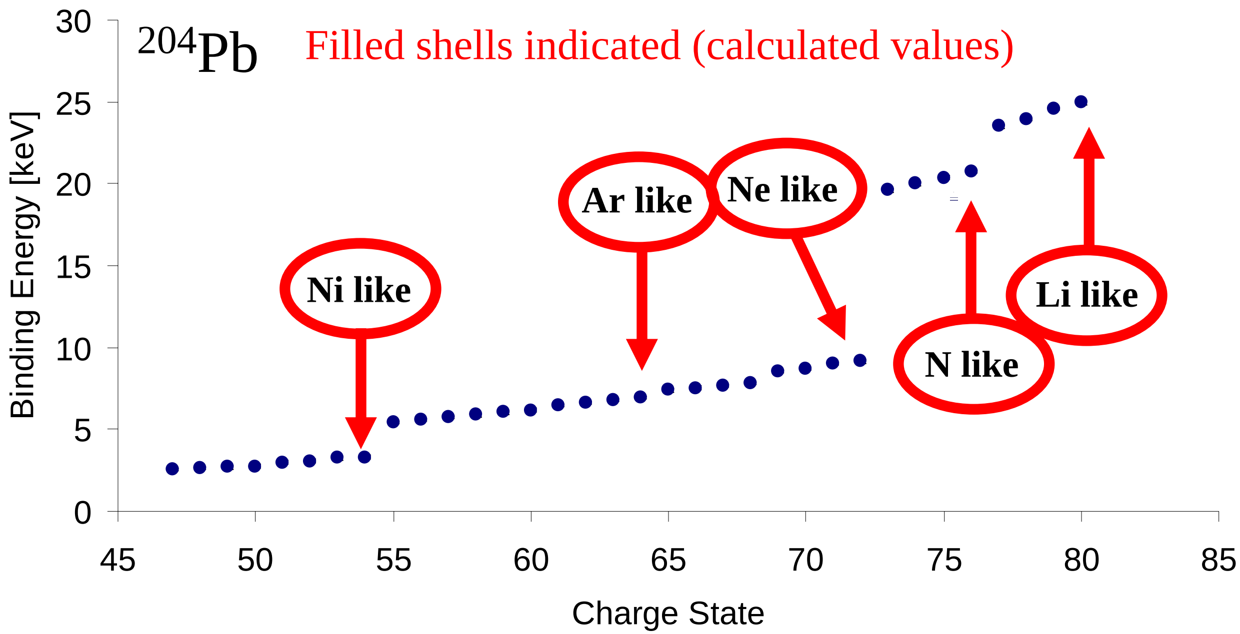
H_2^+ ➔ EB = -15.4 eV = 8.3 ppb

$^{208}Pb^{50+}$ ➔ E_B = -50.372 keV = 260 ppb

$^{208}Pb^{72+}$ ➔ E_B = -172.177 keV = 889 ppb

Electron binding energies (E_B) are needed to calculate the mass of a neutral atom:

$$M_A = \frac{1}{R}\frac{q}{q_{ref}} - qm_e - E_B(A^{q+})$$

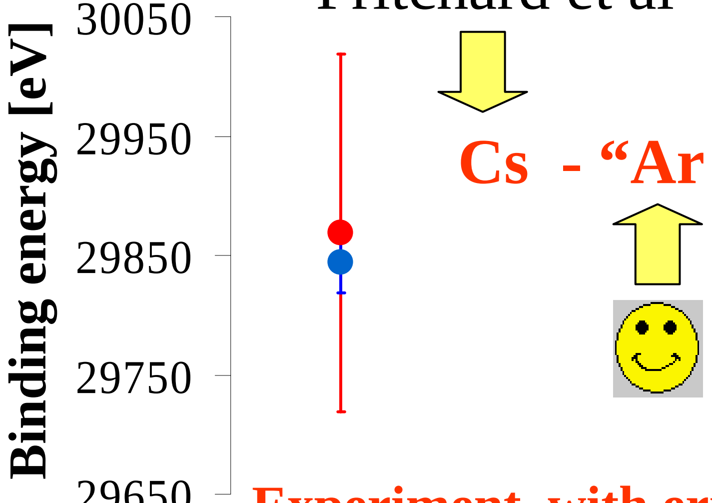


Examples where calculations are used (tested)

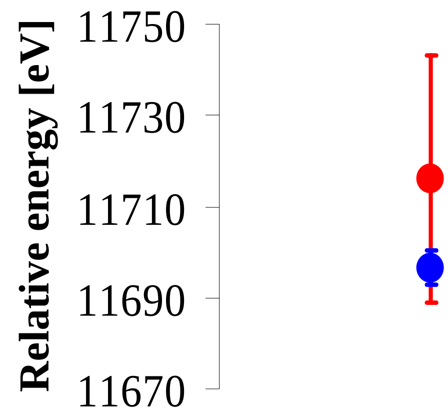
Measure :Hg^{52+} (..$3d^{10}$), Add: 52 m_e and E_B= -56 377(50) eV

Binding energy 56377.66 eV uncertainty ~50 eV = 0.5 ppb
Scofield’s values deviates 2 ppb   SMILETRAPs mass=2 ppb

Pritchard et al



Cs - “Ar - like” Cs



“Al - like” - “Cl - like” Cs

Experiment with error bars
and Theory with size of correlation

Conclusion

- **The mass is a fundamental property that is of importance in many fields in physics**

- **With SMILETRAP almost any stable mass can be measured with an uncertainty <1 ppb**

  In a few case an accuracy close to $\mathbf{10^{-10}}$ have been reached

- **Next mass determinations :**
  - Some mass(es) in the mercury region such as Ta, Pb, ^{232}Th or ^{235,238}U to solve the mass table dilemma
  - Test of QED in strong fields, ^{40}Ca for g-factor measurement
- **High precision measurements of e^- binding energies :**
  - Almost any heavy and highly charged atom, mass >100 u
  - 0.2 ppb (~20 eV for mass 100) uncertainty in energy is within reach
  - Test of theoretical calculations

$$M_A = \frac{1}{R}\frac{q}{q_{REF}} m_{REF} + q m_{e^-} - E_B(A^{q+})$$

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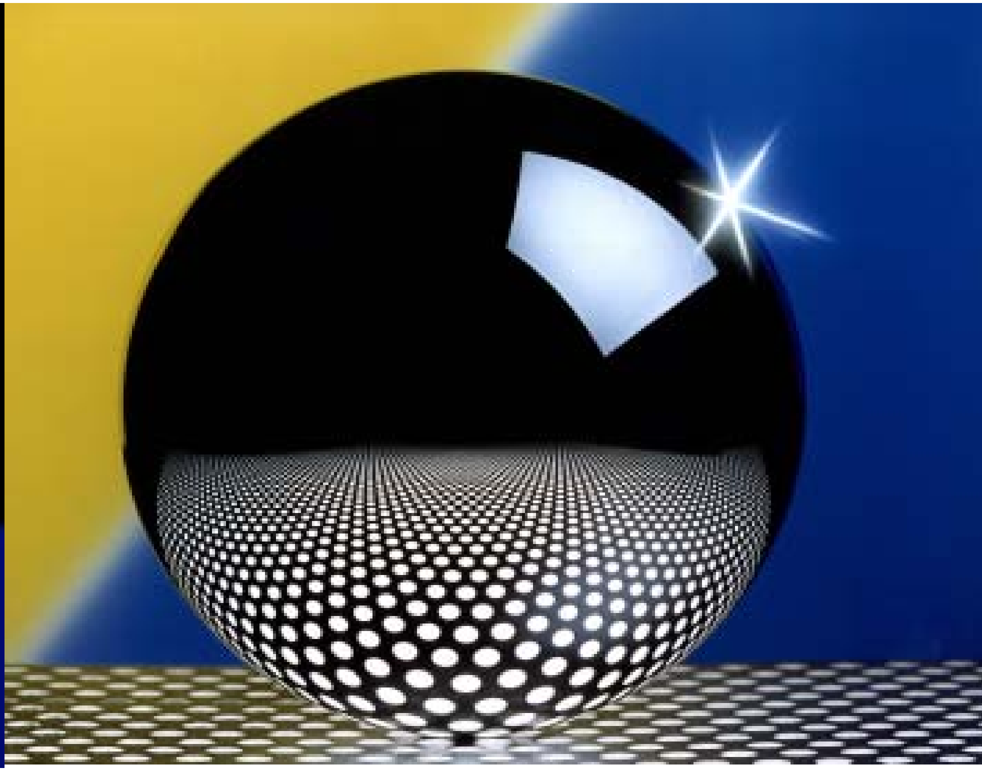
- ^{28}Si for New Definition of Kilogram Mass Standard



^{28}Si 1×10^{-10} direct measurement by MIT

^{29}Si and ^{30}Si 1×10^{-9} indirectly determined

Avogadro Constant

$$Na = \frac{M(Si)\cdot\rho}{\frac{Vo}{n}}$$

M(Si) molar mass of silicon

ρ the density of the silicon body

Vo the volume and n the number of atoms of a unit cell

SMILETRAP: ^{28}Si $\sim3\times10^{-10}$ using HCI

^{29}Si and ^{30}Si should also be measured or a pure ^{28}Si crystal can be used