Ion traps for clocks and other metrological applications

• Single ion clocks vs. neutral atom lattice clocks

• Storage of electrically charged particles in a rf trap
  • Two dimensional trap
  • Paul trap in 3d
  • Penning trap

• Optical atomic clocks based on stored ions
  • Yb
    • Hyper Ramsey Spectroscopy
  • Quantum logic clock
  • Secondary representations of the second

• Other applications of ion traps
  • Microwave frequency standard for deep space applications
  • Mass spectrometry
Principle of (optical) atomic clocks

Absorber (ions, atoms, molecules)

oscillator ↓

Optical clockwork: femtosecond laser

servo - electronics

detector

Accuracy: How accurately agrees $v_{out}$ with $v_0$?

Stability: To what extent fluctuates $v_{out}$ around $v_0$?
Noise and instability

Measure of instability (Allan deviation):

\[
\sigma_y(\tau) = \frac{1}{K} \frac{1}{Q} \frac{1}{S/N} \frac{1}{\sqrt{\tau/s}}
\]

6\cdot10^5 Cs atoms, \(\nu = 9.2\) GHz, \(\Delta\nu = 1\) Hz: \(\sigma_y(t) \approx 4\cdot10^{-14} \tau^{-1/2}\)

Single Yb ion, \(\nu = 688\) THz, \(\Delta\nu = 3.1\) Hz: \(\sigma_y(t) \approx 5\cdot10^{-15} \tau^{-1/2}\)

10^4 neutral Sr atoms, \(\nu = 429\) THz, \(\Delta\nu = 2\) Hz: \(\sigma_y(t) \approx 5\cdot10^{-17} \tau^{-1/2}\)
Single ion and neutral atom optical clocks

**Single ion clock**

- Electrodynamically (Paul) trapped ions
  - Single ions can be confined in field-free center
  - Trapping time: \( \infty \)
  - Low S/N; limited frequency stability

**Neutral atom lattice clock**

- \( 10^4 - 10^6 \) atoms can be interrogated
- High S/N; high frequency stability
- Limited trapping time (seconds)

**Quantum logic clock**

- Perform spectroscopy on \( \text{Al}^+ \)
- Transfer internal state to \( \text{Be}^+ \)
- Detect on \( \text{Be}^+ \)

* Courtesy of P. Schmidt (QUEST) *

NIST (Boulder) operating, PTB, NPL, Innsbruck, ... under construction
Achievable fractional instability

Assuming:
- Cs fountain: $10^5$ Cs atoms; $T_{int} = 1$ sec
- Yb$^+$ ion: $T_{int} = 10$ sec
- $10^4$ Sr atoms: $T_{int} = 0.5$ sec

![Graph showing achievable fractional instability for different systems over varying time scales.](image)
Ion Traps

Consider an electric field configuration \( \vec{E}(\vec{r}) \) defined by a potential \( \Phi(\vec{r}) \) leading to a force on an ion with charge \( q \) at any space point inside the trapping volume pointing to the centre of this volume. In the following we consider singly charged ions, where the charge is \( q = +e = 1.602 \times 10^{-19} \) A s. The force on the ion is

\[
\vec{F}(\vec{r}) = e\vec{E}(\vec{r}) = -e \cdot \nabla \Phi(\vec{r}).
\] (10.1)

Here, \( \nabla = (\partial/\partial x, \partial/\partial y, \partial/\partial z) \) denotes the Nabla operator, used to determine the gradient of a vector field in Cartesian coordinates. Preferentially, this force should increase linearly with the distance \( r \) from the centre \( \vec{F}(\vec{r}) \propto r \) since in this case the particles are expected to perform simple harmonic oscillations. The corresponding scalar potential \( \Phi(x, y, z) \) has a parabolic shape and may be represented by

\[
\Phi = \text{const} \cdot (ax^2 + by^2 + cz^2)
\] (10.2)

with the constant to be determined later. From Laplace’s equation \( \Delta \Phi = \nabla^2 \Phi = 0 \) for regions of space where there is no charge density we derive the condition

\[
a + b + c = 0
\] (10.3)

for the constants determining the potential (10.2).

In the following, we will have a closer look to two particular solutions fulfilling (10.3), namely

\[
a = 1, b = -1, c = 0 \quad \text{(linear quadrupole configuration)} \quad (10.4)
\]
and

\[
a = b = 1, c = -2 \quad \text{(three-dimensional quadrupole configuration).} \quad (10.5)
\]
**Figure 10.1:** The two-dimensional quadrupole potential in the $x - y$ plane can be generated by four electrodes of hyperbolic shape (dark areas).
Paul Trap (Mechanical Analogue Model)


Wolfgang Paul
Nobel prize 1989
Realisations of linear traps generating a radial quadrupole potential with two additional ring electrodes a) or with additional rods b) for axial confinement.
Linear ion trap (Innsbruck design 2000)

\[ \omega_z \approx 0.7 - 2 \text{ MHz} \quad \omega_{x,y} \approx 1.5 - 4 \text{ MHz} \]
Linear Paul Trap

Consider an ion near the centre of the trap experiencing a time-dependent force according to (10.8). The time-dependent position and velocity components can be obtained from the resulting equations of motion of the ion

\[
F_x(t) = m\ddot{x}(t) = eE(x) \cos \omega t = \frac{e}{r_0^2} (U_{dc} - V_{ac} \cos \omega t) x
\]

\[
F_y(t) = m\ddot{y}(t) = eE(y) \cos \omega t = -\frac{e}{r_0^2} (U_{dc} - V_{ac} \cos \omega t) y
\]

where, as usual, the shorthand \( \ddot{x}(t) \) represents \( d^2x/dt^2 \). Using (10.7) and the dimensionless parameters

\[
\tau = \frac{\omega}{2} t, \quad a = \frac{4eU_{dc}}{m\omega^2 r_0^2}, \quad q = \frac{2eV_{ac}}{m\omega^2 r_0^2}
\]

the equations of (10.9) lead to Mathieu’s differential equation \(^2\)

\[
\frac{d^2 x(\tau)}{d\tau^2} + (a - 2q \cos 2\tau) x = 0
\]

and

\[
\frac{d^2 y(\tau)}{d\tau^2} - (a - 2q \cos 2\tau) y = 0.
\]

Since the coefficients of Mathieu’s equation (10.11) are periodic functions of \( \tau \) there exists a so-called Floquet-type solution \([59, 526]\) of the form
Linear strings of ions

From: Innsbruck group
Figure 2-3: Schematic of a surface-electrode ion trap. The ion trap electrodes are shown at the bottom of the figure in red (RF) and black (DC). Ions are trapped at the origin of the coordinate system shown. The secular potential is plotted on a linear color scale as a function of x and y, with blue representing the lowest and red representing the highest secular potential values.

From: Leibrandt: Integrated chips and optical cavities for trapped ion quantum information processing, Thesis MIT 2009
Penning Trap

Static electric field
+ static magnetic field

\[ \frac{m \ddot{r}}{r} = e \bar{E}(\vec{r}) + e \vec{r} \times \vec{B}, \]
\[ m \ddot{x} = e (E_x + y B_z) \]
\[ m \ddot{y} = e (E_x - x B_z) \]
\[ m \ddot{z} = e E_z. \]

Oscillatory motion in \( z \)

\[ \omega_z^2 = \frac{4eU_{dc}}{m(r_0^2 + 2z_0^2)} \]

from: \( e \vec{v} \cdot \vec{B} = m \frac{\vec{v}^2}{r} \)

Cyclotron frequency

\[ \omega_c = \frac{e}{m} B_z \]

from: \( e E_{rad} = e \vec{v} \cdot \vec{B} \)

Magnetron frequency

\[ \omega_m = \frac{E_r}{Br} \]
Ion Motion in Penning Trap

Oscillatory motion $\omega_z$

Magnetron frequency $\omega_m$

Cyclotron frequency $\omega_c$

$B_z$
Radio Frequency (Paul) Trap

end cap

ring electrode

\[ z_0 \]

\[ r_0 \]
Quantum jump spectroscopy

absorption and emission cause fluorescence steps (digital quantum jump signal)

Quantum jump technique
Electron shelving technique

Observation of quantum jumps:
Nagourney et al., PRL 56, 2797 (1986),
Sauter et al., PRL 57, 1696 (1986),
Bergquist et al., PRL 57, 1699 (1986)
The number of observed dark phases taken from data like that of previous transparency as a function of their duration allows one to fit an exponential decay and to determine the lifetime of the long-lived state.

From: E. Peik: Laserspektroskopie an gespeicherten Indium-Ionen. Dissertation MPQ 181, Max-Planck-Institut für Quantenoptik, 1993
Side-band cooling

Absorption spectrum of the 281.5 nm transition in a single 198Hg+ ion before (inset) and after side-band cooling using 194 nm radiation.
Courtsey of D. Wineland, with permission
Yb$^+$ single ion clock

- E3: Insensitive to external fields
- E3: Extremely long natural lifetime
  - low instability
  - huge light shift has been suppressed by Hyper-Ramsey-Technique


Courtesy of N. Huntemann, PTB
Partial energy diagram of Yb\(^+\). Dashed lines (411 nm, 435 nm and 467 nm) represent the optical transitions proposed for optical frequency standards. The 369 nm line is used for cooling and detection.

The spectrum of the transition of a single Yb\(^+\) ion in a Paul trap shows besides the carrier the motional sidebands along the radial \((r1\ and\ r2)\) and axial \((z)\) directions. Courtesy of Chr. Tamm.
Currently smallest estimated uncertainty of any optical clock (comparable to Al\(^+\) NIST \((8.6 \times 10^{-18})\), Sr JILA \((6.4 \times 10^{-18})\))

Similarly low statistical uncertainties would require \(
\sim 300 \text{ h}\) measuring time (could be reduced by a smaller experimental line width; requires more stable laser)

Required: comparison of two Yb\(^+\) clocks with such an uncertainty

<table>
<thead>
<tr>
<th>Effect</th>
<th>(\delta \nu / \nu_0 \times 10^{-18})</th>
<th>(u / \nu_0 \times 10^{-18})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackbody radiation shift @298 K</td>
<td>-70.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Second-order Doppler shift</td>
<td>-5</td>
<td>2.5</td>
</tr>
<tr>
<td>Light shift from the probe laser</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Quadratic dc Stark shift</td>
<td>-1.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Quadrupole shift and tensorial second-order dc Stark shift</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Second-order Zeeman shift</td>
<td>-36</td>
<td>1</td>
</tr>
<tr>
<td>Servo error</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>AOM chirp</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>-113.2</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Accurate measurement of differential polarizability and temperature measurement in the trap

With Hyper-Ramsey technique

Estimated uncertainty budget of PTB’s Yb\(^+\) clock (E3)

Courtesy of N. Huntemann
Temperature radiation at the location of the ion

- Measurement with temperature sensors at a copy of the trap and FEM by P. Balling und M. Doležal (CMI)
  → effective temperature rise $\Delta T = 2(1) \text{ K}$
- Combination with measurement of ambient temperature
  → Frequency shift by thermal radiation
  $= -70.7(2.6) \times 10^{-18}$

Courtesy of N. Huntemann
“Hyper-Ramsey”-Spectroscopy (HRS)

- Compensation of the light shift $\Delta L$ by detuning $\Delta S$ of the clock laser during interrogation
- Additional $\pi$ pulse removes linear behaviour of $\Delta L - \Delta S$
  $\rightarrow$ considerable suppression of light shift

Experimental investigation of HRS

- Real time stabilization of frequency jump $\Delta_S$ guarantees $(\Delta_L - \Delta_S) = 0$

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition</th>
<th>Frequency wavelength / μm</th>
<th>Natural linewidth / Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{138}\text{Ba}^+$</td>
<td>$5d \ 2D_{3/2} - 5d \ 2D_{5/2}$</td>
<td>24 012 048 317 170 Hz</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$6s \ 2S_{1/2} - 5d \ 2D_{5/2}$</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>170.1 THz</td>
<td>0.005</td>
</tr>
<tr>
<td>$^{88}\text{Sr}^+$</td>
<td>$5s \ 2S_{1/2} - 4d \ 2D_{5/2}$</td>
<td>444 779 044 095 510(50) Hz</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>$4s \ S_{1/2} - 3d \ D_{5/2}$</td>
<td>0.674</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>411 THz</td>
<td>0.13</td>
</tr>
<tr>
<td>$^{171}\text{Yb}^+$</td>
<td>$6s^2S_{1/2} - 5d^2F_{7/2}$</td>
<td>642 121 496 772.6(1.2) kHz</td>
<td>$5 \times 10^{-10}$</td>
</tr>
<tr>
<td></td>
<td>$6s^2S_{1/2} - 5d^2D_{3/2}$</td>
<td>0.467</td>
<td></td>
</tr>
<tr>
<td>$^{171}\text{Yb}^+$</td>
<td>$6s^2S_{1/2} - 5d^2D_{5/2}$</td>
<td>688 358 979 309 312(6) Hz</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.435</td>
<td></td>
</tr>
<tr>
<td>$^{171}\text{Yb}^+$</td>
<td>$6s^2S_{1/2} - 5d^2D_{5/2}$</td>
<td>729 487 779 566(153) kHz</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.411</td>
<td></td>
</tr>
<tr>
<td>$^{115}\text{In}^+$</td>
<td>$5s^2 \ 1S_0 - 5s5p \ 3P_0$</td>
<td>1 267 402 452 899.92(23) kHz</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2365</td>
<td></td>
</tr>
<tr>
<td>$^{199}\text{Hg}^+$</td>
<td>$6s^2S_{1/2} - 5d^9s^2 \ 2D_{5/2}$</td>
<td>1 064 721 609 899 143(10) Hz</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.282</td>
<td></td>
</tr>
</tbody>
</table>
Principle of the Al\textsuperscript{+} Clock

Laser Oscillator

Frequency Feedback

Quantum Logic State Detection

fs-comb

I(f)

280 THz = 1070 nm

\( \frac{2P_{3/2}}{2P_{1/2}} \)

\( \frac{2D_{5/2}}{2D_{3/2}} \)

\( \frac{2S_{1/2}}{1P_1} \)

\( \frac{3P_1}{3P_0} \)

\( \frac{267nm}{167nm} \)

\( \frac{729nm}{866nm} \)

\( \frac{854nm}{397nm} \)

\( \frac{866nm}{854nm} \)

\( \frac{27Al^+}{40Ca^+} \)

\( I = 0 \) Courtesy of P. Schmidt

\( I = 5/2 \)
Quantum logic ion technique

a) Clock ion and logic ion are in their electronic and motional ground states.
b) Excitation of the clock ion.
c) A $\pi$ pulse detuned to the blue motional sideband maps the excitation amplitudes $\alpha$ and $\beta$ of the clock ion onto the motional states of the clock ion and, as a result of the entanglement, the logic ion.
d) A $\pi$ pulse detuned to the red motional sideband maps $\alpha$ and $\beta$ on the electronic states of the logic ion.
Frequency Comparison of Two High-Accuracy $\text{Al}^+$ Optical Clocks

C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband

Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA
(Received 23 November 2009; published 17 February 2010)

We have constructed an optical clock with a fractional frequency inaccuracy of $8.6 \times 10^{-18}$, based on quantum logic spectroscopy of an $\text{Al}^+$ ion. A simultaneously trapped $\text{Mg}^+$ ion serves to sympathetically laser cool the $\text{Al}^+$ ion and detect its quantum state. The frequency of the $^1S_0 \leftrightarrow ^3P_0$ clock transition is compared to that of a previously constructed $\text{Al}^+$ optical clock with a statistical measurement uncertainty of $7.0 \times 10^{-18}$. The two clocks exhibit a relative stability of $2.8 \times 10^{-15} \tau^{-1/2}$, and a fractional frequency difference of $-1.8 \times 10^{-17}$, consistent with the accuracy limit of the older clock.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Shift ($10^{-18}$)</th>
<th>Uncertainty ($10^{-18}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess micromotion</td>
<td>$-9$</td>
<td>$6$</td>
</tr>
<tr>
<td>Secular motion</td>
<td>$-16.3$</td>
<td>$5$</td>
</tr>
<tr>
<td>Blackbody radiation shift</td>
<td>$-9$</td>
<td>$3$</td>
</tr>
<tr>
<td>Cooling laser Stark shift</td>
<td>$-3.6$</td>
<td>$1.5$</td>
</tr>
<tr>
<td>Quad. Zeeman shift</td>
<td>$-1079.9$</td>
<td>$0.7$</td>
</tr>
<tr>
<td>Linear Doppler shift</td>
<td>$0$</td>
<td>$0.3$</td>
</tr>
<tr>
<td>Clock laser Stark shift</td>
<td>$0$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>Background-gas collisions</td>
<td>$0$</td>
<td>$0.5$</td>
</tr>
<tr>
<td>AOM freq. error</td>
<td>$0$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>Total</td>
<td>$-1117.8$</td>
<td>$8.6$</td>
</tr>
</tbody>
</table>
Al⁺ clock (instability and accuracy)

\[ \frac{f(\text{Al}^+)}{f(\text{Hg}^+)} = 1.052871833148990438(55) \]

\[ f(\text{Hg}^+) = 1\,064\,721\,609\,899\,145.30(69) \text{ Hz.} \]

\[ \frac{f(\text{Al}^+)}{f(\text{Hg}^+)} = 1.052871833148990438(55) \]

T. Rosenband et al, Science 319 (2008), 1808 - 1812
Influence of special relativity

1905 "Zur Elektrodynamik bewegter Körper"

Principle of relativity:
Laws of Physics are the same in all inertial systems

c = const:
The speed of light has in each inertial system (in vacuum) the same value (c = 299 792 458 m/s).

Space and time are no longer absolute!

\[ \Delta t = \Delta t' \sqrt{1 - \frac{v^2}{c^2}} \]

**Time dilation:**
Moved clocks slow down
Al$^+$ quantum logic clock - relativistic tests (I)


Relativistic time dilation
Theory of General Relativity

Theory of general relativity (1915)
from inertial systems of special relativity
to accelerated systems

Equivalence principle:
Gravitation and acceleration are equivalent

Result:
Gravitation modifies space (curvature) and
slows down time

\[ R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu} \]

Curvature of space  
Fundamental constants  
Matter (density, pressure,..)

Large mass (sun, earth)
Metric tensor

$$ds^2 = g_{\alpha\beta} (x^\mu) \, dx^\alpha \, dx^\beta$$

*metric tensor in a suitable coordinate system* $(x^\mu) = (x^0, x^1, x^2, x^3)$

Metric tensor for a non-rotating geocentric coordinate system:

$$g_{00} = -\left(1 - \frac{2U}{c^2}\right), \quad g_{0j} = 0, \quad g_{ij} = \left(1 + \frac{2U}{c^2}\right) \delta_{ij}$$

with $U = U_{\text{Earth}} + U_{\text{Tide}}$: Newtonian gravitational potential

$$U_E = \frac{G M_E}{r} + J_2 G M_E a_1^2 \left(1 - 3 \sin^2 \phi \right) \frac{1}{2 r^3}.$$  

$$ds^2 = -\left(1 - \frac{2U}{c^2}\right) c^2 dt^2 + \left(1 + \frac{2U}{c^2}\right) \left[ (dx^1)^2 + (dx^2)^2 + (dx^3)^2 \right]$$

Near Earth’s surface the approximation holds

$\Delta U \sim g \, h$ with $g \sim 9.81$ m/s$^2$ and $h$: height

$\Delta v/v \sim g \, h / c^2 \sim 1.1 \cdot 10^{-16} \, h$
In the future a new definition for the second will be required.
Secondary representations of the second

In 2001 CCTF has established a working group, that developed the concept, procedures and recommendations (now CCL – CCTF WGFS).

• Optical and other microwave standards were expected to demonstrate reproducibility and stability approaching that of primary caesium

• Such systems could be used to realise the second, provided their accuracy was close to that of caesium

• Adoption as such secondary representations would help with detailed evaluation of reproducibility of these standards at the highest level

• Their uncertainty could obviously be no better than the caesium uncertainty

• This activity was likely to significantly aid the process of evaluation of different standards in preparation for a possible future redefinition of the second
Criteria for a secondary representation

1) The SI value of the unperturbed frequency of a quantum transition suitable as a secondary representation of the second must have an uncertainty that is evaluated and documented so as to meet the requirements adopted for the primary frequency standard for use in TAI.

2) This uncertainty should be no larger than about a factor of 10 of the primary standards of that date that serve as the best realisations of the second.
## Secondary Representations of the Second

<table>
<thead>
<tr>
<th>System</th>
<th>Studied at</th>
<th>Value / Hz (CIPM 2012)</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{27}\text{Al}^+$</td>
<td>NIST, PTB</td>
<td>1 121 015 393 207 857.3</td>
<td>1.9 x 10$^{-15}$</td>
</tr>
<tr>
<td>$^{199}\text{Hg}^+$</td>
<td>NIST</td>
<td>1 064 721 609 899 145.3</td>
<td>1.9 x 10$^{-15}$</td>
</tr>
<tr>
<td>$^{171}\text{Yb}^+$ (E2)</td>
<td>PTB, NPL</td>
<td>688 358 979 309 307.1</td>
<td>3 x 10$^{-15}$</td>
</tr>
<tr>
<td>$^{171}\text{Yb}^+$ (E3)</td>
<td>PTB, NPL</td>
<td>642 121 496 772 645.6</td>
<td>1.3 x 10$^{-15}$</td>
</tr>
<tr>
<td>$^{88}\text{Sr}^+$</td>
<td>NPL, NRC</td>
<td>444 779 044 095 485.3</td>
<td>4.0 x 10$^{-15}$</td>
</tr>
<tr>
<td>$^{87}\text{Sr}$</td>
<td>PTB, SYRTE, U. Tokyo, JILA, NIMJ, NPL, ...</td>
<td>429 228 004 229 873.4</td>
<td>1 x 10$^{-15}$</td>
</tr>
<tr>
<td>$^{171}\text{Yb}$</td>
<td>NIST, ...</td>
<td>518 295 836 590 865.0</td>
<td>2.7 x 10$^{-15}$</td>
</tr>
<tr>
<td>$^{87}\text{Rb}$</td>
<td>SYRTE, NPL, ...</td>
<td>6 834 682 610. 904 312</td>
<td>1.3 x 10$^{-15}$</td>
</tr>
</tbody>
</table>

These optical clocks can be used alternatively to the Cs clock, but can never have an uncertainty better than the Cs clock.
Application 1: Deep Space Atomic Clock

- SST-US Orbital Test Bed (OTB)
- DSAC Hosted Payload
- Commanding & Telemetry
- Host Ground Network
- US Air Force Space Test Program (STP II) (Falcon Heavy)

Int’l GNSS Service (IGS):
- ~400 GPS tracking stations globally
- IGS timescale (ensemble clock w/ ~5.e-16 stability)
Microwave Ion Trap ({}^{199}\text{Hg}^+) 

In the Jet Propulsion Laboratory ultra-stable frequency standards [based on linear traps with typically $10^6$ to $10^7$ 199Hg$^+$ ions pumped by a 202Hg rf discharge lamp and cooled with He buffer gas to near room temperature.}
Microwave Ion Trap ($^{199}$Hg$^+$) for deep space applications

In an extended linear trap ions are transferred between two confinement regions one for production and detection of the ions and one for Ramsey excitation. The contribution of the fractional second-order Doppler shift was estimated to be $-4 \times 10^{-13}$.

$2.29 \text{ cm} \times 26 \text{ cm} \times 23 \text{ cm}; 17.5 \text{ kg}; 44 \text{W}$

From: https://directory.eoportal.org/web/eoportal/satellite-missions/d/dsac
Microwave Ion Trap ($^{199}\text{Hg}^+$) for deep space applications

Figure 11. Allan deviation of frequency residuals between LITS-9 and JPL maser SAO-26, showing improved short-term stability. The stability is maser-limited for times greater than $10^4$ seconds.
Application 2: Linear Paul Trap as Mass Filter

Linear Paul Trap as Mass Filter

Resolving power $\frac{m}{\Delta m} = 6500$

Ion Trap Mass Spectrometry in Space

- Comets are small bodies that orbit the sun in our solar system
- Comets comprise of “rock, dust and ice”
- Nucleus is smaller than 50km, the tail (coma, etc.) can be very large – up to 150 million km (larger than the sun)
- Comets are usually very “dark” objects: only few % of mass reflect light
- Comets consist of material formed at the formation of the earth (+ other planets) “frozen in time” (4600 million years ago)

Comet Hale Bopp (03/21/97)

Ptolemy Instrument and the Rosetta Space Mission

J.F.J. Todd, S.J. Barber et al.
*J. Mass Spectrom.* 2007; 42; 1-10
Rosetta Mission

- Launched Mar 2004 on Ariane 5G+ in Kourou, French Guyana
- Designed to meet up with comet Churyumov – Gerasimenko (‘67P’) in 2014
- 3000kg launched (100 kg lander, 165 kg scientific instruments)
- Fly-by several other comets until the landing
- Fully automatic landing
- Total cost: $ 970-980 million
Ptolemy Instrument on Rosetta Lander

- Helium Tanks
- Electronics Box
- Small Bore Reactors
- Mass Spectrometer
- Vent pipe
- Hydrogen and Helium Manifolds
- Chemistry Manifolds and Large Bore Reactors
- Sample Pipe
- GC Bobbin
- Power connection
Mass Spectrometer of Ptolemy

Measure $^2$H, $^{13}$C, $^{15}$N, $^{17}$O and $^{18}$O relative to specified reference

http://ptolemy.open.ac.uk/frames.htm
Application 3: Mass spectrometer for neutrino rest

$M(^3\text{H})$ and $M(^3\text{He})$ measurements have implications for direct neutrino mass measurement:

$$m_n \approx 2.24 \text{ eV} \quad (97\%C.L.)$$

The KATRIN experiment plans improved (sub-eV) limits on $m_n$.

Independent mass difference measurements give a check on systematic errors, and potentially remove a free parameter from the data analysis.

Neutrino mass effects the $\beta$-decay spectrum:

$$\frac{dN}{dE} \propto e^2 (E_{\beta} - E_{\text{rest}})^3 \frac{1}{\sqrt{E_{\beta} - E_{\text{rest}}}}$$

$E_{\beta}$ and $E_{\text{rest}}$ describe the electron final state

$E_{\beta} = E_{\text{rest}} = (m_n^2 - m_{\text{He}})^2$ is the total reaction energy, where $E_{\text{rest}}$ is the daughter atom's final state energy, and $E_{\beta} - m_{\text{He}}$ is the minimum beta-electron energy.

$m_n$ is the average mass for the $\beta$.

KATRIN: Karlsruhe Tritium Neutrino Experiment (75 m long)

http://depts.washington.edu/uwptms/pics/dp7-neutrino.png
Ion traps for clocks and other metrological applications

- Single ion clocks vs. neutral atom lattice clocks

- Storage of electrically charged particles in a rf trap
  - Two dimensional trap
  - Paul trap in 3d
  - Penning trap

- Optical atomic clocks based on stored ions
  - Yb
    - Hyper Ramsey Spectroscopy
  - Quantum logic clock
  - Secondary representations of the second

- Other applications of ion traps
  - Microwave frequency standard for deep space applications
  - Mass spectrometry