Trapped Ions 2:
Scalability & quantum metrology

Alastair Sinclair
National Physical Laboratory, Teddington

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Outline

Ion trap scalability
- Challenge for quantum technology
- Example systems under study
- Case study of a microtrap

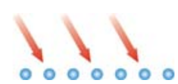
Trapped ions for precision measurements
- Atomic clocks
- Variation of fundamental constants
- Quantum logic clock

1. Ion trap scalability

Ion trap quantum computing

Power of quantum information processing
- as problem size grows, required resources grow in manageable way
- useful technology must control large quantum systems
- in practice this means thousands of qubits (for now)

First proposal for trapped ion QIP
- Cirac & P. Zoller, PRL 74, 4091 (1995)
- string of ions in a single trap
- qubit logic levels: electronic states
- mutual Coulomb interaction: mechanism for transferring quantum information between ions
- ….. many more details from lectures of Christian Roos



DiVincenzo Criteria

Necessary conditions for any viable QIP technology platform
1. a scalable physical system of well-characterised qubits
2. the ability to initialise the state of the qubits to a simple state
3. long (relative) decoherence times
4. a universal set of quantum gates
5. a qubit-specific measurement capability

Necessary conditions for QIP "networkability"
1. the ability to interconvert stationary and flying qubits
2. the ability to faithfully transmit flying qubits between specified locations

Scalability

Scaling to large number of ions
- single trap: presents huge technical difficulties
- probably limited to ~10 → ~20 ions in practice
- centre of mass mode: ω_z breathing mode: $\sqrt{3}\omega_z$

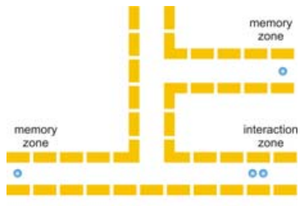
"*Architecture for a large-scale ion trap quantum computer*"
D Kielpinski, C Monroe, D J Wineland, Nature, 417, 709 (2002)

Quantum charged-coupled device (QCCD)
- architecture consisting of many interconnected traps
- few ions in any one trap
- shuttle ions between traps
- uses quantum manipulation techniques already developed

Quantum CCD

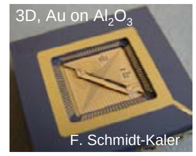
"*Architecture for a large-scale ion trap quantum computer*"
D Kielpinski, C Monroe, D J Wineland, Nature, 417, 709 (2002)

- segmented array of many interconnected ion traps
- QI held in memory zone
- shuttle ions to interaction zone
- ions held close together → Coulomb coupling
- focused laser drives entangling gate
- ions transported to other zone
- ready for next operation

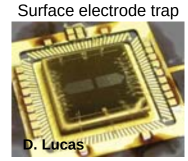


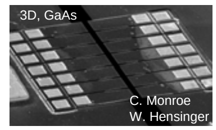
Segmented ion trap arrays:examples

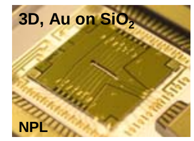
Many different technical approaches……



Surface electrode trap







…. by a number of different groups

Hensinger (Sussex) group review: M D Hughes, et al, arXiv:1101.3207v2 [quant-ph]

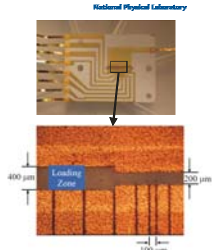
Gold on alumina microtrap

Al_2O_3 wafer

- laser-machined electrode structure
- evaporate Au coating
- electroplate to ~few μm thickness
- assemble layers into 3D structure

Very successful in QIP demonstrations

- M D Barrett *et al.* Nature 429, 737 (2004): teleportation
- many other QIP experiments from Wineland group



courtesy D. Wineland, NIST

Junction: W K Hensinger *et al*, Appl Phys Lett 88, 034101 (2006)

- "T"-junction and 2D array: 3-layer trap

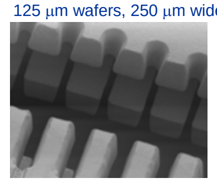
State of the art: R B Blakestad *et al*, Phys Rev Lett 102, 153002 (2009)

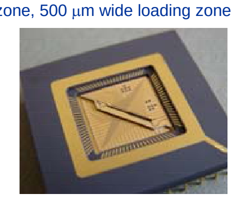
- "X"-junction and 2D array: high fidelity transport

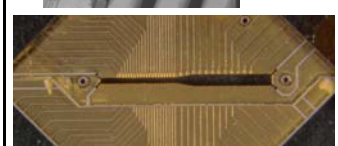
Gold on alumina microtrap

F. Schmidt-Kaler, Univ. Mainz

- 125 μm wafers, 250 μm wide processor zone, 500 μm wide loading zone







courtesy: F Schmidt-Kaler

$\omega_r/2\pi \leq 2.0$ MHz
$\omega_z/2\pi \leq 1.2$ MHz
trap depth = 0.75 eV

S A Schulz, *et al,*
New J Phys 10, 045007 (2008)

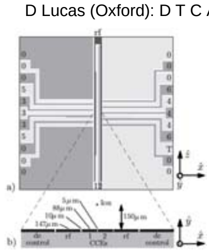
Surface electrode ion trap arrays

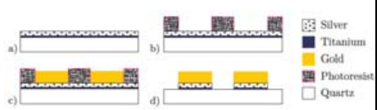
Wineland group: S. Seidelin, *et al*, Phys Rev Lett 96, 253003 (2006)

All electrodes lie in a single plane (2D)

- significant simplification in fabrication

D Lucas (Oxford): D T C Allcock, *et al*, New J Phys 12, 053026 (2010)



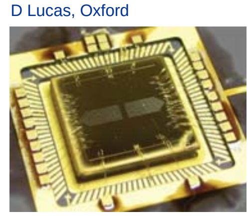


a) Evaporation of Ag\Ti seed layer
b) Lithographic definition of electrode template
c) Electroplating of gold electrodes
d) Template and seed layer etch

courtesy: D Lucas

Surface electrode ion trap arrays

D Lucas, Oxford



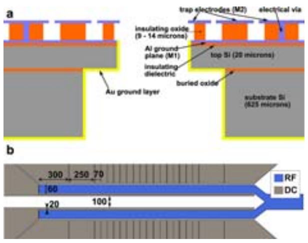
courtesy: D Lucas

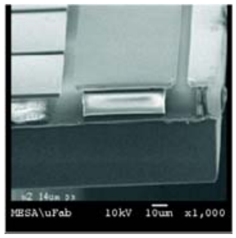
r_o = 150 μm
$\Omega_{RF}/2\pi$ = 25.8 MHz
112 V ≤ U_{RF} ≤ 223 V
2.0 MHz ≤ $\omega_r/2\pi$ ≤ 4.0 MHz
300 kHz ≤ $\omega_z/2\pi$ ≤ 1.2 MHz
Trap depth: 47 to 188 meV
Ion Lifetime (typical): 5 min

D T C Allcock, *et al*,
New J Phys 12, 053026 (2010)

Surface electrode ion trap arrays

D Moehring, D Stick, M Blaine, (Sandia Labs)





courtesy: D L Moehring

Single ion shuttling

- 10 electrodes, 770 µm, 10^6 times, without loss
- 1.5 km @ 0.77 m/s

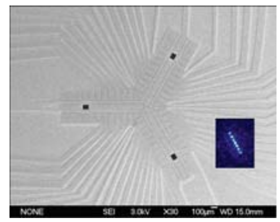
D Stick, *et al*, arXiv:1008.0990v2 [physics.ins-det]

Surface electrode ion trap arrays

D Moehring, D Stick, M Blaine, (Sandia Labs)

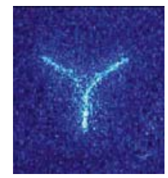
"Y"-shaped junction trap

- High-fidelity single ion shuttling
- Ion string: splitting, swapping, recombining



courtesy: D L Moehring

40 µm in each arm
10 sec exposure
40,000 round trips



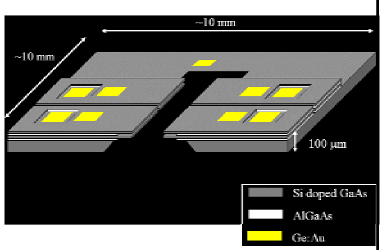
D L Moehring, *et al*, arXiv:1105.1834v1 [quant-ph]

Monolithic 3D microtrap

Monroe group: D. Stick, *et al*, Nature Phys, 2, 36 (2006)

MEMS GaAs microtrap

- AlGaAs & GaAs layers
- GaAs conductor for electrodes

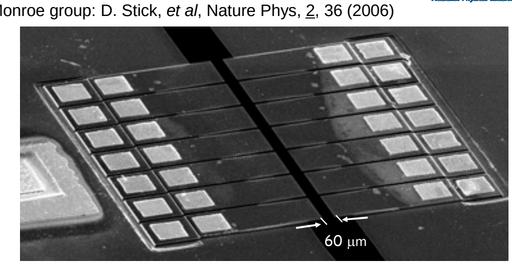


Segment width = 130 µm
Aperture width = 60 µm
Layer thickness = 2→4 µm
Trap depth ~ 80 meV
Ion lifetime (uncooled) ~ 100 ms

courtesy: Winni Hensinger & Chris Monroe

MEMS GaAs 3D microtrap

Monroe group: D. Stick, *et al*, Nature Phys, 2, 36 (2006)



courtesy: Winni Hensinger & Chris Monroe

Segment width = 130 µm
Aperture width = 60 µm
Layer thickness = 2→4 µm
Trap depth ~ 80 meV
Ion lifetime (uncooled) ~ 100 ms

Other activity

Wineland group (NIST), surface traps:

- J M Amini *et al*, New J Phys 12, 033031 (2010)
- 150 zones, 6 "Y" junctions
- hexagonal circuit configuration

Wineland group (NIST), "degenerate" silicon traps:

- J Britton *et al*, Appl Phys Lett 95, 173102 (2009)
- surface and 3D (assembled) configurations

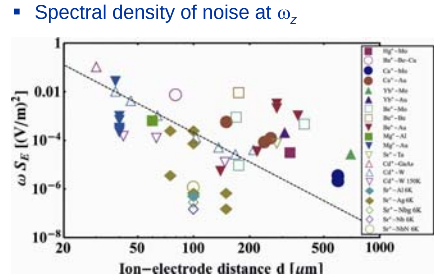
Chuang group (MIT) group, "surface" traps:

- J Labaziewicz,*et al*, Phys Rev Lett 100, 013001 (2008)
- silver on quartz
- cryogenic temperatures: reduced heating rate

Measured heating rates

Heating is due to electric field noise on electrodes

- Spectral density of noise at ω_z



$$\dot{n} = \frac{e^2 S_E(\omega_z)}{4 m \hbar \omega_z}$$

$$S_E(\omega) \propto \frac{1}{d^4}$$

Graph courtesy of Winni Hensinger, Sussex

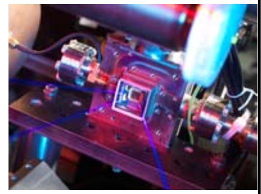
Turchette *et al*, Phys. Rev. A 61, 063418 (2000)
Deslauriers *et al*, Phys. Rev. A 70, 043408 (2004)

2. Microtrap case-study

A microfabricated ion trap

From idea to reality

- Concept of the microtrap
- Design considerations
- Fabrication
- How does it perform?
- First ion trapping results
- Future uses



Microtrap concept: 1

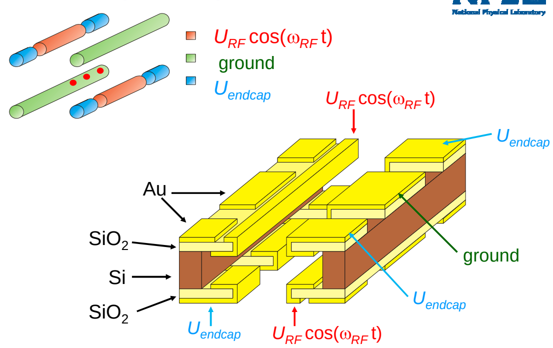
Aims: desirable attributes

- long ion storage times → easier trap operation
- high motional frequencies → fast gates & qubit processing
- precise geometry → ideal behaviour
- scalability → towards large number of ions
- minimised dielectric surfaces → minimum stray charges

Requirements

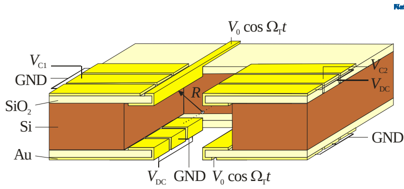
- **3D, unit-aspect ratio** geometry
- monolithic fabrication process
- lithographic techniques **extended to 3D**
- low rf power dissipation: eg Au on SiO_2

Microtrap concept: 2



M Brownnutt, G Wilpers, P Gill, R C Thompson, AS, New. J. Phys. 8, 232 (2006)

Microtrap concept: 2



- highly doped silicon wafer (350 µm) → grounded spacer surface
- oxidised surfaces (15 µm fused silica) → low loss insulator
- gold electrodes in 3D → low loss conductor
  → efficient electrode geometry
  → dielectric surfaces covered

Brownnutt, *et al*, N J Phys. 8, 232 (2006)

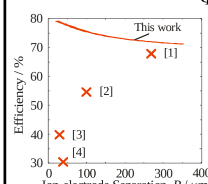
Trap potential modelling

Use finite element modelling (2 & 3D)

Trap Efficiency, η_{trap}

- compare microtrap potential with a quadrupole potential (hyperbolic electrodes) of comparable size.
- ratio of quadrupole part of potential in a microtrap to a hyperbolic trap potential of same r_o

$$\eta_{trap} = \frac{\Phi^{(2)}_{microtrap}}{\Phi_{hyperbolic}} \qquad \omega_r = \eta_{trap}\frac{eU_{RF}}{\sqrt{2}m\omega_{RF}r_o^2}$$

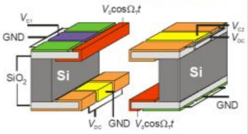


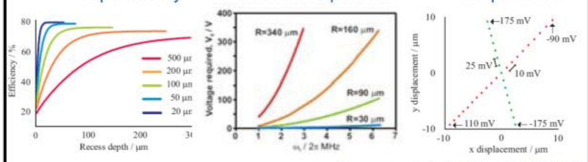
[1] 2-layer Al_2O_3 trap. (Wineland)
M.A. Rowe *et al*., Quant. Inf. Comp. 2, 257 (2002)
[2] 3-layer Al_2O_3 trap. (Monroe)
W.K. Hensinger *et al.*, App Phys Lett 88, 034101 (2006)
[3] GaAs High aspect ratio trap. (Monroe)
D. Stick *et al*., Nature Physics 2, 36 (2006)
[4] Surface Trap. (Wineland),.
S. Siedelin *et al*., PRL 96, 253003 (2006)

Trap modelling

Finite element modelling in 2D & 3D shows

- high trap efficiencies,
- minimised distortion from recessed Si ,
- high motional frequencies at realistic voltages,
- micromotion compensation achievable.



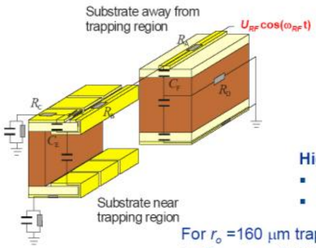


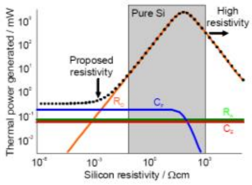
Brownnutt, *et al*, N J Phys. 8, 232 (2006)

RF dissipation

Substrate heating

- resistive heating of Au & Si
- RF heating of SiO_2.





High conductivity bulk Si

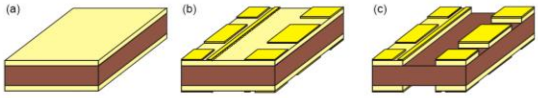
- ρ_0 = 0.0026 Ωcm
- Grounded "spacer" surface

For r_o =160 µm trap, expect:

- $P_{dissipated}$ ~ few mW, ΔT ~ 10°C heating of Au & Si
- $P_{dissipated} \propto r_o^4$ →smaller traps not limited by RF heating

Fabrication overview

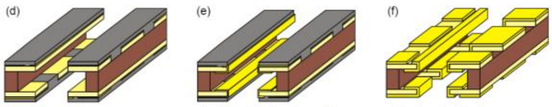
start process with highly doped n-Si wafer



(a) thermal oxidation: 28 days

(b) surface electrode pattern: evaporation

(c) oxide pattern: oxide etch



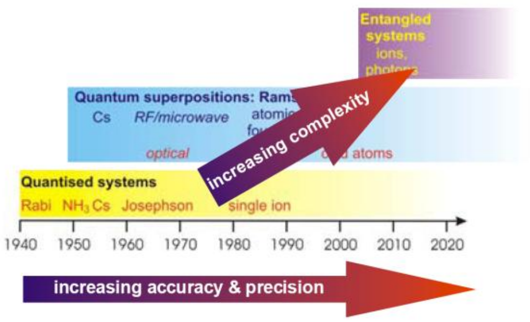
(d) Si etch and recess: DRIE

(e) inside electrode pattern: shadow evaporation

(f) electrode thickness: electroplating

3. Trapped ion atomic clocks

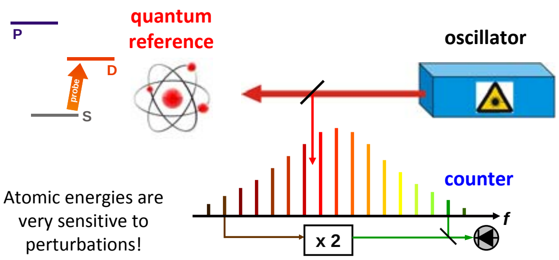
Evolution of quantum metrology



Atomic clocks

Quantised energies in atomic systems

- $E = \hbar\omega_o$: natural definition of frequency & time
- References at microwave and optical frequencies



Atomic energies are very sensitive to perturbations!

Some definitions

Short term (in)stability

- a measure of the extent by which ν_{out} fluctuates about ν_o
- ν_{out} is the locked local oscillator (*i.e.* laser) frequency
- dominated by the local oscillator

instability: $\sigma(\tau) = \dfrac{\Delta\nu}{\pi\nu_o} \cdot \left[\dfrac{T}{N\tau}\right]^{\frac{1}{2}}$

atomic Q-factor: $Q = \dfrac{\nu_o}{\Delta\nu}$

signal-to-noise: $(s/n) = \left[\dfrac{N\tau}{T}\right]^{\frac{1}{2}}$

- T is cycle time (time to make a single correction to ν_{laser})
- N is no. of absorbers detected in a cycle, τ is averaging time

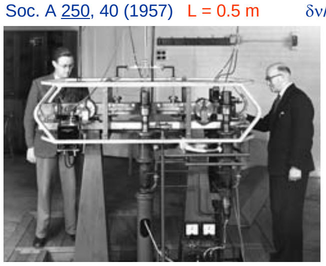
Accuracy

- How well does ν_{out} agree with the unperturbed theoretical ν_o?
- dominated by longer-tern reproducibility of the atomic reference
- absolute uncertainty is measured against primary Cs standard

Cs beam clock

L Essen & J V L Parry at NPL:

Phil. Trans. R. Soc. A 250, 40 (1957) L = 0.5 m $\delta\nu/\nu = 1\times10^{-10}$



Increase the distance between resonators

- Increase the free precession time T $\Rightarrow$ reduce linewidth

Nature 184, 1792 (1959) L = 2.8 m $\delta\nu/\nu = 1\times10^{-11}$

Why optical?

Current primary frequency standards

- based on 9.2 GHz hyperfine transition in ^{133}Cs atoms (fountain)
- accuracy ~ 10^{-15} with >1 day of averaging time
- systematic $\delta\nu/\nu = 4.1\times10^{-16}$

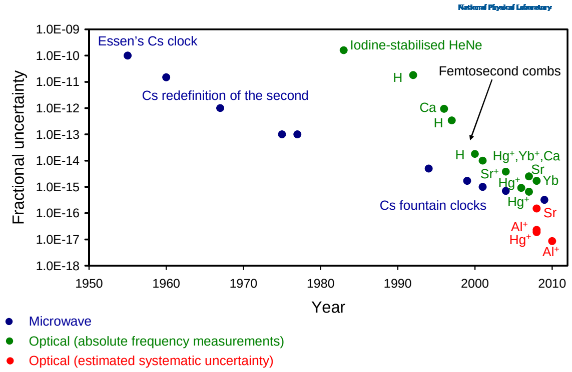
eg: K. Szymaniec, *et al*, Metrologia 47, 363 (2010)

clock instability: $\sigma \propto \dfrac{\Delta\nu}{\nu_o} \cdot \dfrac{1}{(s/n)}$

Optical frequency standards

- based on forbidden transitions in atomic particles, $\Delta\nu$ ~ 1 Hz
- frequencies: ν ~ 10^{15} Hz
- optical resonance Q-factor: $\Delta\nu/\nu$ ~ 10^{15}
- results in better stabilities than microwave clocks
- projected uncertainty: can be down to 10^{-17} and better

Quantum frequency standards



Why ions for a reference?

A single, laser-cooled, trapped ion is….

- an isolated particle, virtually at rest, unperturbed by its environment

Desirable features

- laser cooled $\rightarrow$ no Doppler-broadening
- Lamb-Dicke confinement $\rightarrow$ minimised 2nd order Doppler shift
- no E-field at trap centre $\rightarrow$ minimised perturbations
- UHV $\rightarrow$ few collisions with background gas
- narrow optical transitions $\rightarrow$ $\Delta\nu \leq 1$ Hz
- long interrogation times $\rightarrow$ 0.1 to 10 s; towards natural linewidth

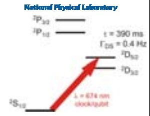
$\Rightarrow$ ideal reference for frequency standard & clock

Review: H S Margolis, J Phys B 42, 154017 (2009)

Choosing an ion reference

1. Identify species with a "long-lived" clock transition

- "forbidden" weak transition with metastable upper level
- $\Delta\nu = 1/2\pi\tau$ (lifetime τ; natural linewidth $\Delta\nu$)
- for $0.1\ \mathrm{s} \le \tau \le 100\ \mathrm{s}$, $2\ \mathrm{Hz} \le \Delta\nu \le 0.002\ \mathrm{Hz}$

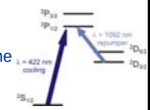


2. Examine sensitivities of transition energy to EM fields

- B-field (Zeeman shift), E-field (Stark shift),
- Blackbody radiation

3. Is there an accessible transition for laser-cooling?

- strong (S→P) dipole transition, short (~ns) P-state lifetime
- rapid scattering rate → efficient cooling



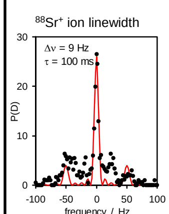
4. Can the cooling cycle be kept sufficiently closed?

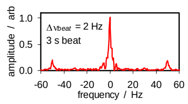
- low branching-ratio for decay out of cooling cycle
- sensible lasers available for repumping?

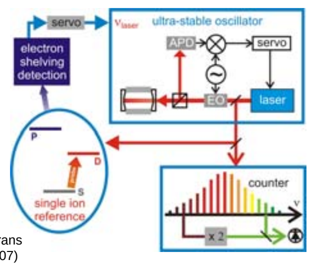
Which ion?

ion	λ_{clock}/ nm	$\Delta\nu_{clock}$/ Hz	$\lambda_{cooling}$ / nm	$\Gamma_{cooling}$ / MHz	Cooling laser source / nm
$^{88}Sr^+$	674	0.4	422	23	844 + shg
$^{40}Ca^+$	729	0.15	397	23	397
$^{171}Yb^+$	436	3	369	20	738 + shg
$^{171}Yb^+$	467	~10^{-9}	369	20	738 + shg
$^{199}Hg^+$	282	1.7	194	70	shg + sfm
$^{115}In^+$	237	0.8	231	0.36	462 + shg
$^{27}Al^+$	267	0.008	167	?	?

Architecture of a single-ion clock

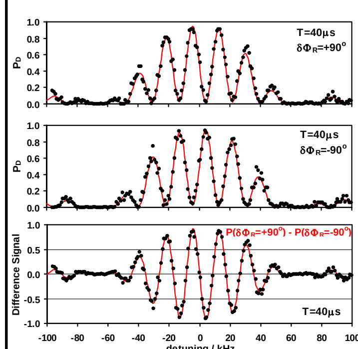


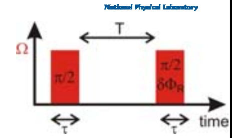




G P Barwood *et al*, IEEE Trans Instrum Meas, **56**, 226 (2007)

Laser stabilisation





modulate $\delta\Phi_R$ from +90° to -90°

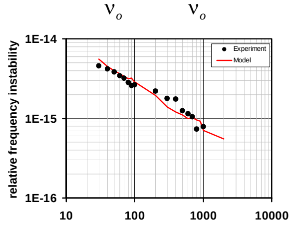
- antisymmetric lineshape
- zero-crossing @ ω_o

V Letchumanan et al, PRA 70, 033419 (2004)
JOSA B 23, 714 (2006)

Comparing two traps

Two traps, each containing a single ion

- measure ν_{ion1}, ν_{ion2}
- calculate $\dfrac{\delta\nu}{\nu_o} = \dfrac{|\nu_{ion1} - \nu_{ion2}|}{\nu_o}$



G P Barwood, G Huang, H A Klein, P Gill, NPL

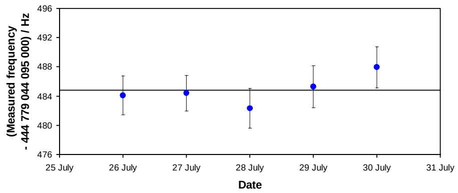
Systematic uncertainties

Source	Method 1		Method 2	
	Shift (Hz)	Uncertainty (Hz)	Shift (Hz)	Uncertainty (Hz)
Statistics	-	**1.3**	-	**1.2**
Quadrupole shift	0	0.5	0	<0.01
2nd order Doppler shift (micromotion)	<0.01	0.01	<0.01	0.01
2nd order Doppler shift (secular motion)	<0.01	0.01	<0.01	0.01
Stark shift (micromotion)	+0.01	0.01	+0.01	0.01
Stark shift (secular motion)	<0.01	0.01	<0.01	0.01
Blackbody Stark shift	+0.30	0.08	+0.30	0.08
1092 nm ac Stark shift	0	0.02	0	0.02
422 nm ac Stark shift	+1.4	0.8	+1.4	0.8
Servo errors	-1.0	0.6	-0.4	0.3
Maser reference frequency	**0**	**0.7**	**0**	**0.7**
Gravitational shift	0	0.1	0	0.1
Total	+0.7	1.9	+1.3	1.6

H S Margolis *et al*, Science 306, 1355 (2004)

Absolute measurement of $^{88}Sr^{+}$

NPL National Physical Laboratory



- Measurements carried out relative to the NPL caesium fountain
- Quadrupole shift nulled by measuring for 3 different values of m_j
- 5 days of data, statistical uncertainty 1.2 Hz

f_{Sr} = 444 779 044 095 484.8 (1.6) Hz

H S Margolis *et al*, Science 306, 1355 (2004)

Absolute ν_{ion} measurements

NPL National Physical Laboratory

ion	λ_{clock}/ nm	$\Delta\nu_{clock}$/ Hz	Fractional uncertainty ($\delta\nu/\nu$) / 10^{-15}	
$^{88}Sr^{+}$	674	0.4	3.8	NPL: H S Margolis *et al*, Science 306, 1355 (2004)
$^{40}Ca^{+}$	729	0.15	2.4	Innsbruck: M Chwalla *et al*, PRL 102, 023002 (2009)
$^{171}Yb^{+}$	436	3	1.1	PTB: Chr Tamm *et al*, PRA 80, 043403 (2009)
$^{171}Yb^{+}$	467	$\sim10^{-9}$	20	NPL: K Hosaka *et al*, PRA 79, 033403 (2009)
$^{199}Hg^{+}$	282	1.7	0.65	NIST: W H Oskay *et al*, PRL 97, 020801 (2006) J E Stalnaker *et al*, Appl Phys B 89, 167 (2007)
$^{27}Al^{+}$	267	0.008	0.65	NIST: T Rosenband *et al*, Science 319, 1808 (2008)

Al^{+}: an useful reference?

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Clock transition

- 267 nm: SHG of SHG of 1068 nm +
- linewidth: $\Delta\nu$ = 8 mHz ++

Systematic frequency shift sensitivities

- smallest known blackbody shift ++
- negligible electric quadrupole shift ++
- linear Zeeman shift, average pair of components +
- Small quadratic Zeeman shift +

Cooling transition

- 167 nm: deep UV, not accessible – – – –

… need to overcome the cooling transition problem for cooling and state readout

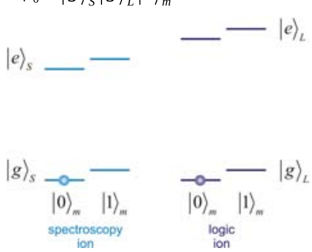
NPL National Physical Laboratory

4. Break?

Quantum logic spectroscopy

NPL National Physical Laboratory

$$\psi_0 = |g\rangle_S |g\rangle_L |0\rangle_m$$



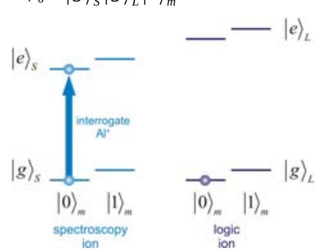
Use logic ion to cool common mode *m* to ground state

P O Schmidt *et al*, Science 309, 749 (2005)

Quantum logic spectroscopy

NPL National Physical Laboratory

$$\psi_0 = |g\rangle_S |g\rangle_L |0\rangle_m$$



Excite spectroscopy ion

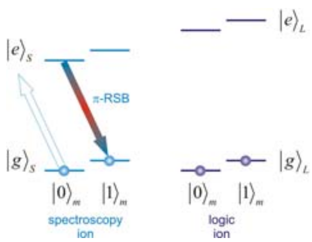
$$\psi_1 = \left[\alpha|g\rangle_S + \beta|e\rangle_S\right]|g\rangle_L |0\rangle_m$$

$$\psi_1 = \left[\alpha|g\rangle_S |0\rangle_m + \beta|e\rangle_S |0\rangle_m\right]|g\rangle_L$$

P O Schmidt *et al*, Science 309, 749 (2005)

Quantum logic spectroscopy

$$\psi_1 = \left[\alpha|g\rangle_S|0\rangle_m + \beta|e\rangle_S|0\rangle_m\right]|g\rangle_L$$



Apply π-pulse on RSB of spectroscopy ion

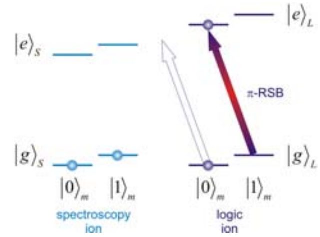
$$\psi_2 = \left[\alpha|g\rangle_S|0\rangle_m + \beta|g\rangle_S|1\rangle_m\right]|g\rangle_L$$

$$\psi_2 = |g\rangle_S|g\rangle_L\left[\alpha|0\rangle_m + \beta|1\rangle_m\right]$$

P O Schmidt *et al*, Science 309, 749 (2005)

Quantum logic spectroscopy

$$\psi_2 = |g\rangle_S|g\rangle_L\left[\alpha|0\rangle_m + \beta|1\rangle_m\right]$$



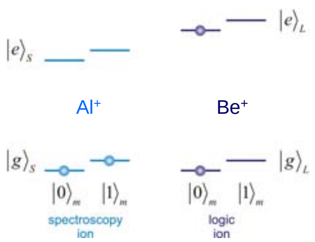
Apply π-pulse on RSB of logic ion

$$\psi_3 = |g\rangle_S\left[\alpha|g\rangle_L + \beta|e\rangle_L\right]|0\rangle_m$$

P O Schmidt *et al*, Science 309, 749 (2005)

Quantum logic spectroscopy

$$\psi_3 = |g\rangle_S\left[\alpha|g\rangle_L + \beta|e\rangle_L\right]|0\rangle_m$$



Initial state of spectroscopy ion

$$\psi_S = \alpha|g\rangle_S + \beta|e\rangle_S$$

mapped to final state

$$\psi_L = \alpha|g\rangle_L + \beta|e\rangle_L$$

of logic ion

….. readout state of logic ion with electron shelving method

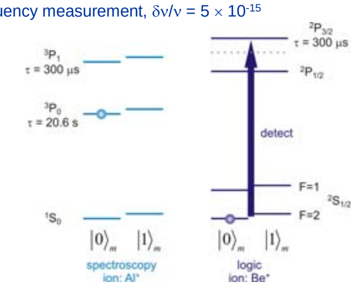
P O Schmidt *et al*, Science 309, 749 (2005)

Al^+ spectroscopy

Observation of $^1S_0 \rightarrow {}^3P_0$ transition

- QL spectroscopy for state readout
- $\Delta\nu$ = 8 mHz
- first frequency measurement, $\delta\nu/\nu = 5 \times 10^{-15}$

T Rosenband *et al*, PRL 98, 220801 (2007)



Al^+ precision

Frequency ratio ν_{Al^+}/ν_{Hg^+}

- fractional uncertainty of 5.2×10^{-17}

T Rosenband *et al*, Science 319, 1808 (2008)

Two Al^+ clock comparison

- relative stability $\sigma(\tau) = 2.8\times10^{-15}\tau^{-1/2}$
- fractional difference $\left|(\nu_{ion1} - \nu_{ion2})/\nu_o\right| = 1.8\times10^{-17}$

C W Chou *et al*, PRL 104, 070802 (2010)

From the introduction……..Cs primary frequency standards

- based on 9.2 GHz hyperfine transition in ^{133}Cs atoms (fountain)
- accuracy ~ 10^{-15} with >1 day of averaging time
- systematic $\delta\nu/\nu = 4.1\times10^{-16}$

……. the key to some new physics and a new definition of the SI second

Fine structure constant

Frequency ratios (of different transitions) depend on α

- optical transitions have varying sensitivities to $\delta\alpha/\alpha$
- Measure frequency ratio over time yields $\dot{\alpha}/\alpha$

Frequency ratio ν_{Al^+}/ν_{Hg^+}

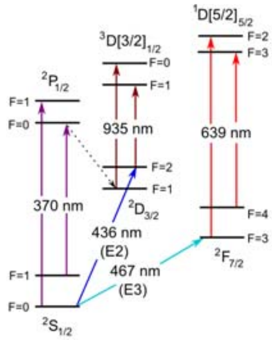
NIST: T Rosenband *et al*, Science 319, 1808 (2008)

$$\rightarrow \dot{\alpha}/\alpha = (-1.6 \pm 2.3)\times10^{-17} / yr$$

2 clocks in one ion

Why $^{171}Yb^{+}$?

- E2 & E3 transitions have large and opposite sensitivities to any time variation of α
- any change in the optical frequency ratio amplifies greatly any change in α
- some systematic shifts (e.g. gravitational redshift, second-order Doppler shift) cancel exactly when ratio is measured in the same, single ion



NPL: R Godun, S King, & P Gill

Al⁺ : time dilation

NIST: C W Chou, D B Hume, T Rosenband, D J Wineland, Science 329, 1630 (2010)

Relativistic time dilation

- ion stationary in clock #1
- ion oscillating ⊥ to laser in clock #2
- detect clock #2 advancing at slower rate for 5 m/s < v_{rms} < 40
- $\delta\nu/\nu_o$ = -7 × 10^{-15} @ v_{rms} = 36 ms, and –4.5 × 10^{-16} @ v_{rms} = 9 ms

Gravitational time dilation

- position of clock #1 fixed and compared to clock #2
- clock #2 height raised by 33 cm
- detect clock #2 advancing at faster rate: $\delta\nu/\nu_o$ = (4.1±1.6) × 10^{-16}

Entanglement-enhanced precision

Limits on measurement precision

- Classical: shot noise limit

$$|\Psi_{in}\rangle = \frac{1}{\sqrt{2}}\left[|S\rangle + |D\rangle\right] \qquad |\Psi_{out}\rangle = \frac{1}{\sqrt{2}}\left[|S\rangle + e^{i\phi}|D\rangle\right]$$

$$\left|\langle\Psi_{in}|\Psi_{out}\rangle\right|^2 = \cos^2(\phi/2)$$

For *N* repeat experiments: **$\Delta\phi = 1/\sqrt{N}$**

- Quantum: Heisenberg limit

$$|\Psi_{in}\rangle = \frac{1}{\sqrt{2}}\left[|S_1\rangle|S_2\rangle....|S_N\rangle + |D_1\rangle|D_2\rangle....|D_N\rangle\right]$$

$$|\Psi_{out}\rangle = \frac{1}{\sqrt{2}}\left[|S_1\rangle|S_2\rangle....|S_N\rangle + e^{iN\phi}|D_1\rangle|D_2\rangle....|D_N\rangle\right]$$

$$\left|\langle\Psi_{in}|\Psi_{out}\rangle\right|^2 = \cos^2(N\phi/2)$$

$\Delta\phi = 1/N$: **$\sqrt{N}$ enhancement**

V Giovannetti, S Lloyd, L Maccone, Science 306, 1330 (2004)

More quantum metrology

Quantum metrology with entangled ions

- High fidelity entanglement on optical transition
- “Designer” atoms: engineered states for specific measurements

…. all the details from Christian Roos next week

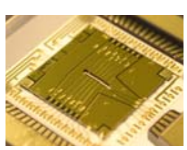
Summary…. microtraps

Scaling up to ion arrays: the DiVincenzo scalability criterion

- Many different technical approaches
- 2D & 3D electrode geometries
- All with microfabrication challenges
- Optical integration is a further challenge

Case-study of NPL microtrap: Au-on-Si0_2-on-Si

- Monolithic, 3D, unit aspect ratio
- Deep potential, long storage times
- Good motional frequencies
- Good electrical characteristics
- Low ion-heating rate



Summary…. metrology

Atomic clocks

- Clock architecture: reference, oscillator, counter
- Optical references & clocks: increased precision
- Single-ion clock components
- Evaluation, systematics, and absolute measurements

Quantum logic spectroscopy

- Powerful technique using QIP-style state mapping
- Used to detect Al clock transition
- Perform metrology at 17th decimal place
- Exciting time for studying physics with unprecedented precision
- ….. the route to redefining definition of time