11.6 Ion traps

So far: neutral atoms

Now: singly charged ions (note: higher charge possible)

Experiments (slides):

- Precision:
  - Electron g factor
  - NIST Quantum logic clock
- Quantum information
  - Entanglement of 14 qubits
  - Quantum computer & simulator
  - Motional control & quantum jumps

Energy scales

Trap potential:

Dipole-trap $U_{dip} = \frac{3\pi c^2}{2\omega_0^3} \frac{\Gamma}{\delta} I \simeq 5 \frac{10 \cdot 10^{16} \frac{m^2}{s^2}}{10 \cdot 10^{45} \frac{1}{s^3}} \times \frac{10^7}{10^{12}} \times \frac{1W}{(10^{6})^2}$

$\omega_0 \sim 2 \cdot 10^{15}$

$= 5 \times 10^{-25} J \simeq 40 mK \approx 750 MHz$

Magnetic trap $U_{mag} = g_F m_F \mu_B B \simeq 10^{-23} \frac{J}{T} \cdot 0.1 T = 10^{-24} J$

Ion trap $U_{ion} = e \cdot V \simeq 10^{-19} C \cdot 100V \simeq 10^{-17} J \simeq 7 \cdot 10^5 K$!

⇒ compared to neutral atoms, ions don't need to be pre-cooled. Trap life time → ∞.

Ion trap geometries

How to build an ion trap?

Problem: $\vec{F} = e\vec{E}$, but $\vec{\nabla} \cdot \vec{E} = 0$ $\left(\text{or } \oint_S \vec{E} \cdot d\vec{A} = 0\right)$

⇒ impossible to create local extrema with static fields! (Earnshaw's theorem)

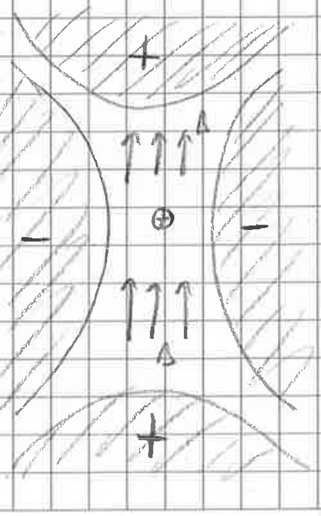
Solution:

- Static electric + magnetic field = Penning trap
- Oscillating electric fields = Paul trap

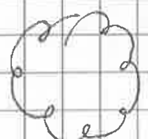
} Nobel Prize 1989

Penning trap

first implementation in 1959 by H. Dehmelt



- hyperbolic electrodes ⇒ z-confinement
- homogeneous B_z ⇒ r-confinement
- ion motion is cycloid: (+ z oscillation)



magnetron: $\omega_m \approx \frac{\omega_z^2}{2\omega_c}$

cyclotron: $\omega_c = \frac{eB}{M}$ ⇒ mass spectrometry

spin: $\Delta\omega_c = g_s eB/2m_e$ ⇒ measure $\frac{g_s}{2}$ at 10^{-11} (1986)

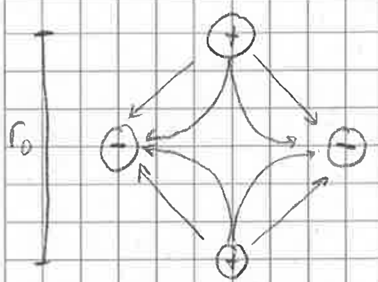
Paul trap

Same electrode configuration

Idea: Switch polarity when ion starts moving towards the anti-confining electrodes.
(Like balancing ball on flat surface)

Linear Paul trap

Consider 4 long electrodes parallel to z



Potential close to symmetry axis

$$\varphi(\vec r) = \varphi_0 - \frac{V_0}{2r_0^2}\cos(\Omega t)(x^2-y^2)$$

$$\Rightarrow \vec E(\vec r) = \frac{V_0}{r_0^2}\cos(\Omega t)(\vec x - \vec y)$$

Equation of motion: $M\ddot x = \frac{eV_0}{r_0^2}\cos(\Omega t)\, x$

Let $\tau = \frac{1}{2}\Omega t \Rightarrow \frac{d^2x}{d\tau^2} = \frac{4eV_0}{\Omega^2 M r_0^2}\cos(2\tau)\, x$ "Mathieu equation"

introduce $q_x = \frac{2eV_0}{\Omega^2 M r_0^2}$ and look for solution of the form

$$x = x_0 \cos(A\tau)\{1 + B\cos 2\tau\}$$

slow oscillation (for $\cos(A\tau)$), fast oscillation "micromotion" (for $B\cos 2\tau$)

$\Rightarrow B = -\frac{q_x}{2}$, $A = \frac{q_x}{\sqrt 2}$ trapping for $q_x \leq 0.9$

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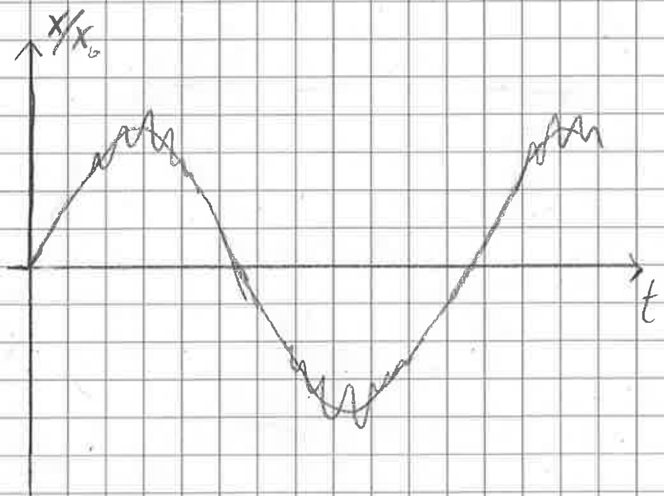


cos(ωt)

Micromotion larger for large excursions

⇒ negligible for cool ions

Trap frequency: $\omega_r = q_x \frac{\Omega}{2\sqrt{2}}$, easily MHz

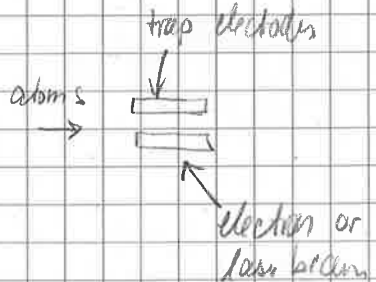
Axial confinement: End caps

Pictures:

- Paul traps (linear, planar ...)
- Ion strings, ion crystals, 2 components

Manipulation of trapped ions

Ionization:



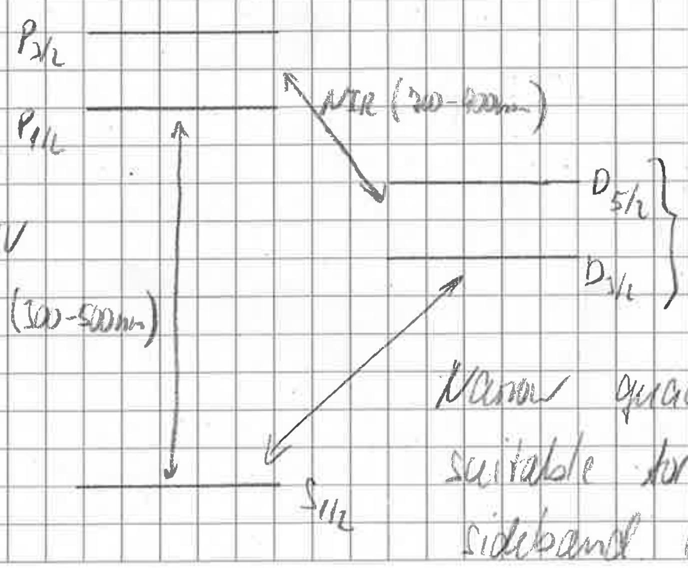
- Electron beam: Works for all species
  Can contaminate potentials
- Laser beam: specific to atom/isotope

e.g. Ca:

Energy-level structure

Preferred are ions of group II: Be, Mg, Ca, Sr, Ba
$\Rightarrow$ hydrogen-like

Typical diagram:



metastable: $\tau \sim 1s$

"Quantum jumps"

Narrow quadrupole transition suitable for quantum logic and sideband cooling.

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Motional states

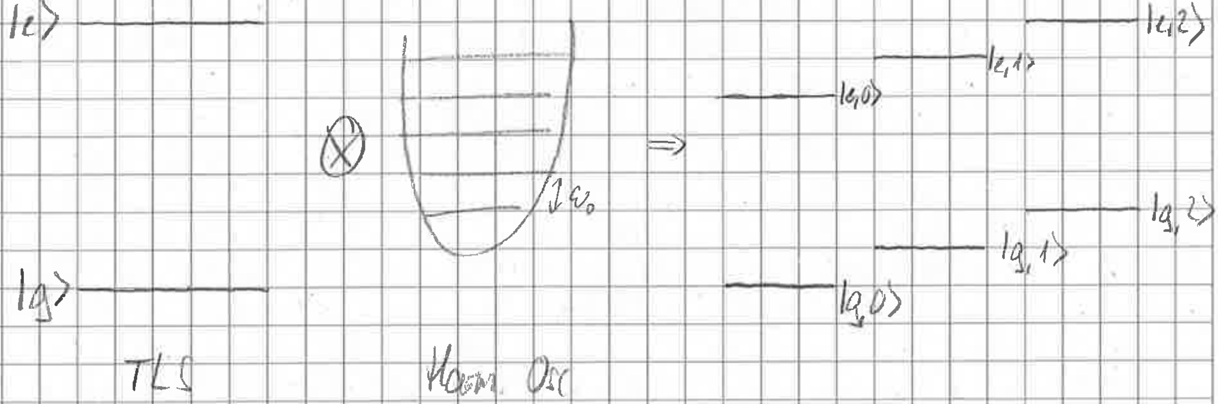
- Ions in the trap repel each other.
- Distance between ions: trapping potential vs. coulomb repulsion
- In 1 dimension: N ions $\Rightarrow$ N normal modes with distinct freq.

Example: 2 ions $\to$ center of mass + breathing

3 ions $\to$ $\underbrace{\text{—''—}}_{\omega_0}$ + $\underbrace{\text{—''—}}_{1.73\omega_0}$ + ? $\quad 2.4\omega_0 \ldots$

Frequencies almost independent of N!

- Addressing via motional sidebands



$\Rightarrow$ Laser that addresses a <u>single ion</u> can selectively excite <u>collective</u> motion

$\Rightarrow$ Multi-qubit gates and entanglement.