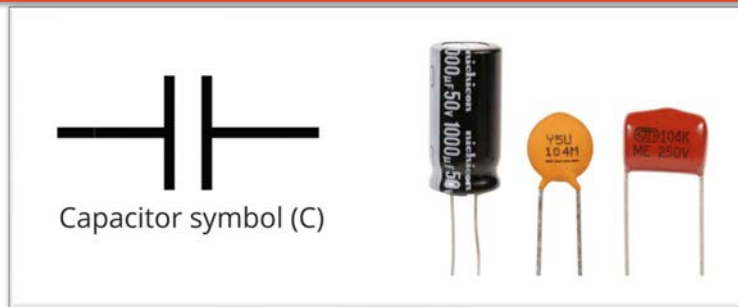


What is a quantum bit?

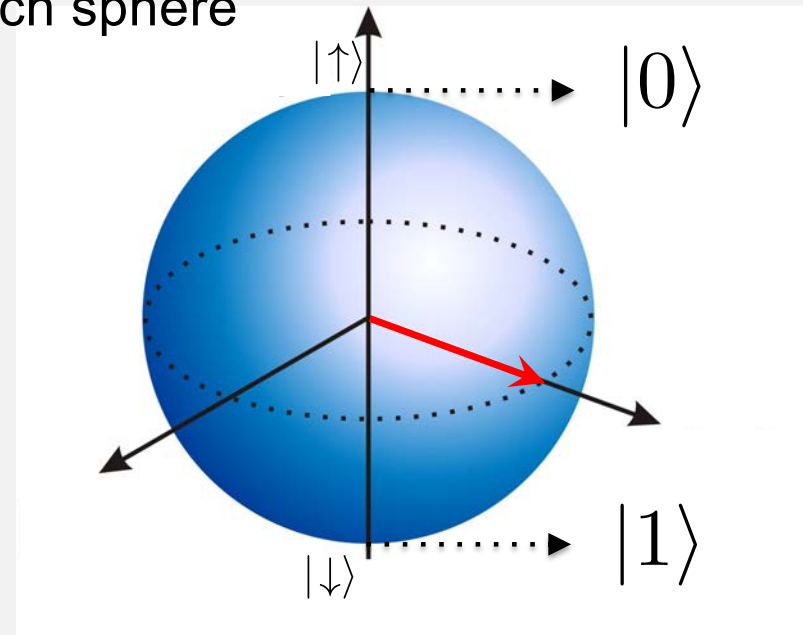
(Classical) *binary digit (bit)*



DRAM

„Qu_(antum) bit“

Bloch sphere



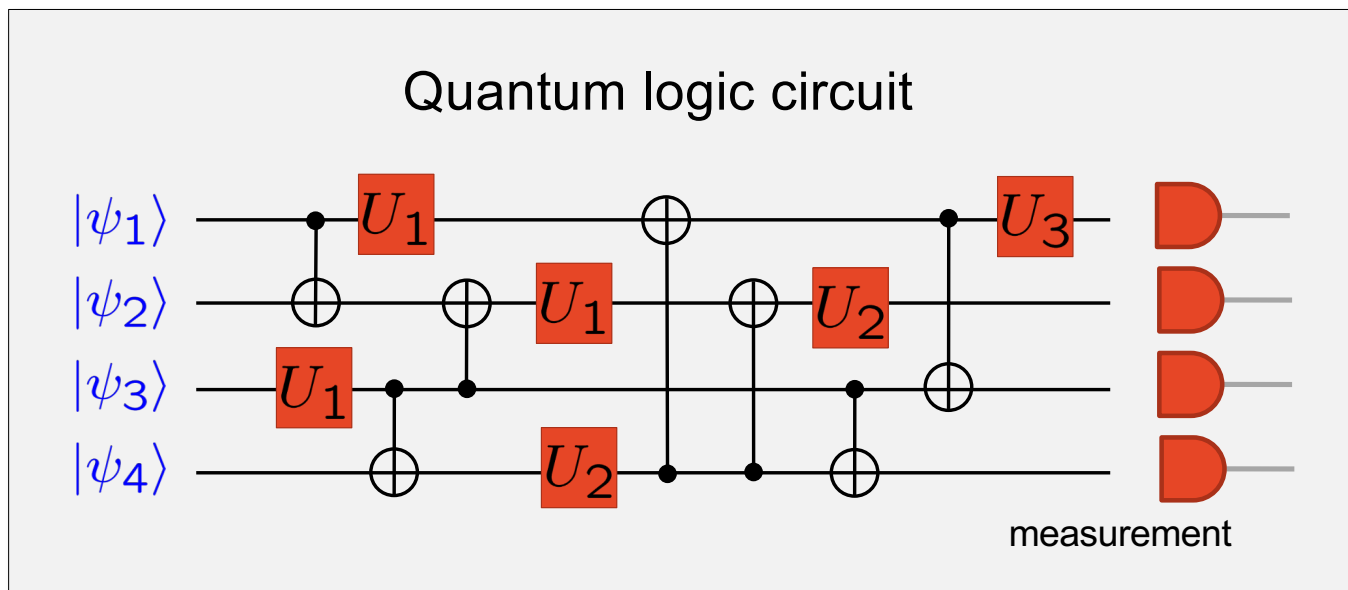
$$\begin{aligned} |\Psi\rangle &= \alpha|0\rangle + \beta|1\rangle & |\alpha|^2 + |\beta|^2 &= 1 \\ &= \alpha|\uparrow\rangle + \beta|\downarrow\rangle \end{aligned}$$

NEW : Superposition & entanglement Page 45

Quantum information processing

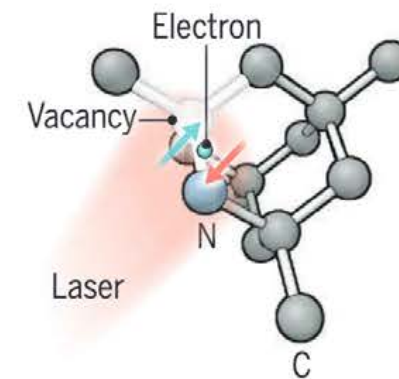
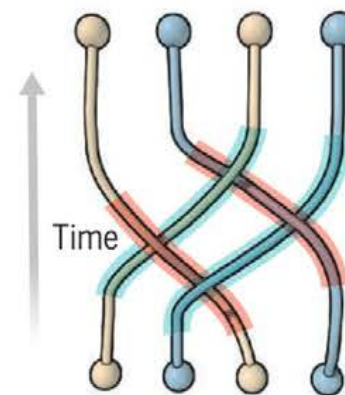
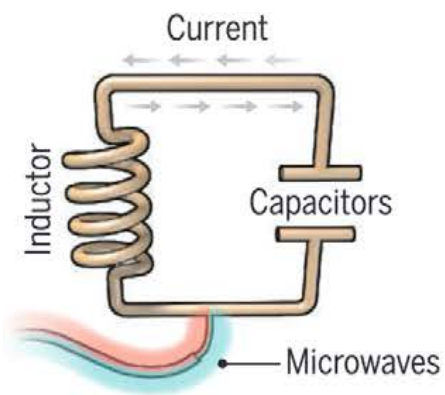
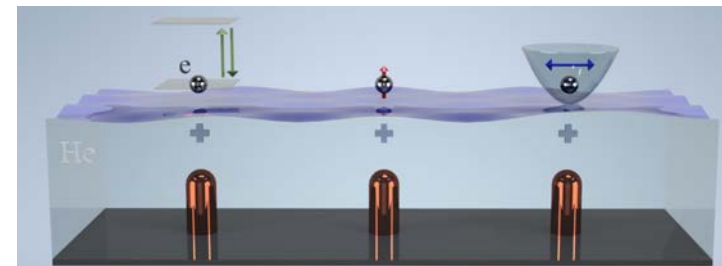
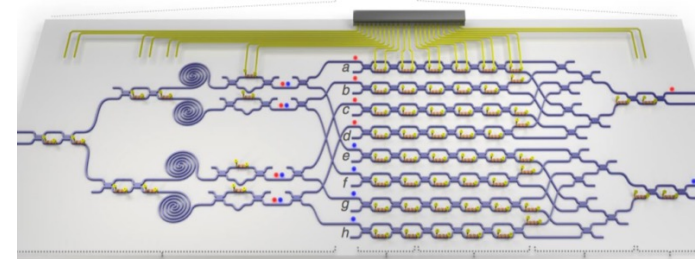
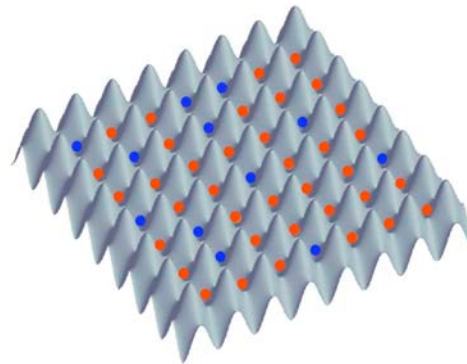
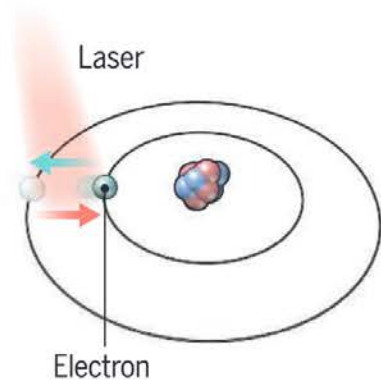
Classical vs. quantum information processing

Quantum circuit



Types of qubits

Modified from Science **354**, 1090 (2016)



Comparison of key metrics (March 2022)

	Superconducting circuits	Trapped ions	
Relaxation time (T1)	15 – 100 μ s	1 s (O)	infinite* (HF)
Phase coherence (T ₂ *)	20 – 100 μ s	500 ms (O)	50 s (HF)
Single qubit gates	$3 \times 10^{-3} - 10^{-4}$	10^{-6} (fid: 99.9999%)	
Gate speed	15 ns	12 μ s	
Two-qubit gates	98.1% - 99.3% (Google) 89.3% - 99.5% (IBM)	10^{-3} (fid: 99.9%)	
Gate speed	10 – 43 ns	1.6 μ s / 30-100 μ s	
Readout fidelity	93.1 – 99.3%	99+ % (99.99%)	
scalability	Medium (size of C and dist)	Hard (complexity, optics+electronics)	
Comment	Inhomogeneous perf.	Homogeneity, but difficult to control	

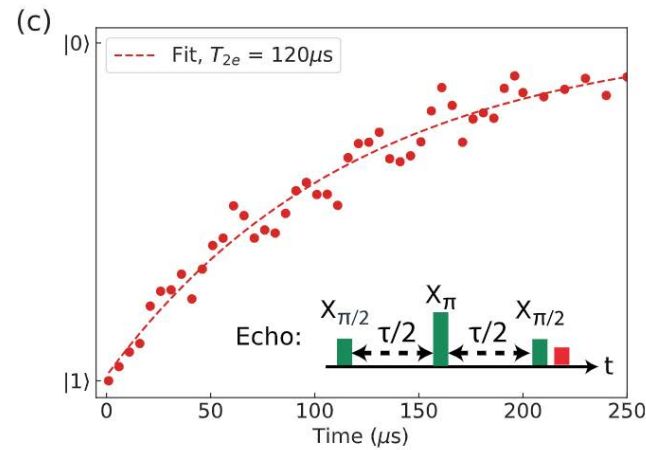
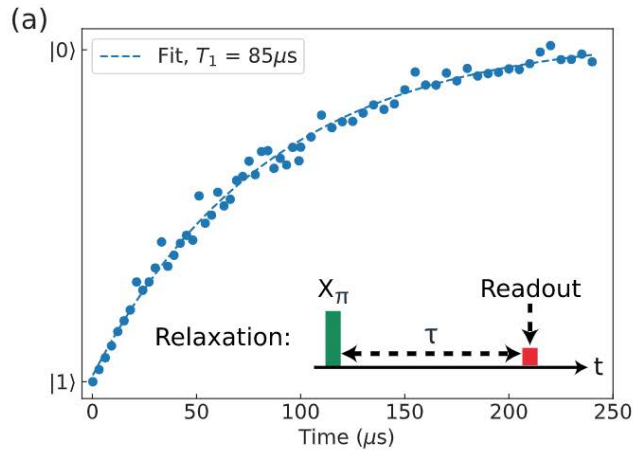
Coherence times in μ s	T1			T2		
	min	max	avg	min	max	avg
IBM Q Kolkata 27	9.86	239.52	126.1 4	11.52	167.8 7	78.64
Google Sycamore	11	21	15	-	-	19

All ions are the same

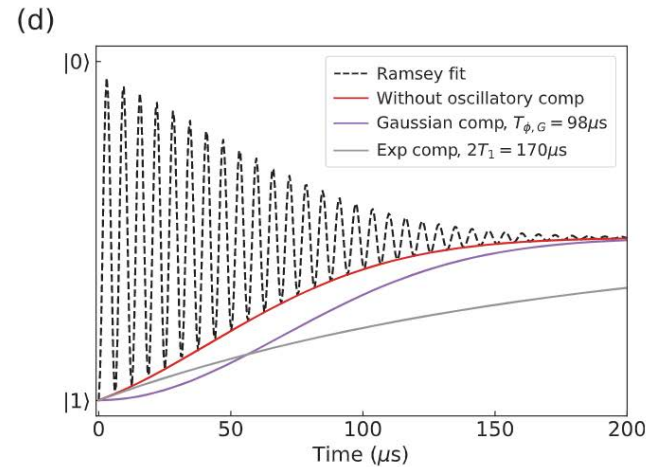
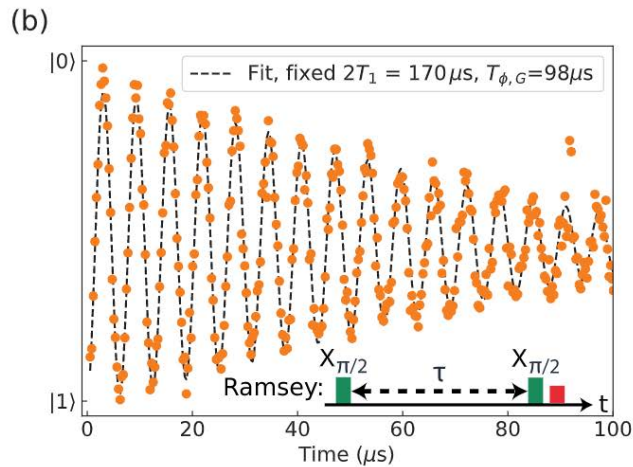
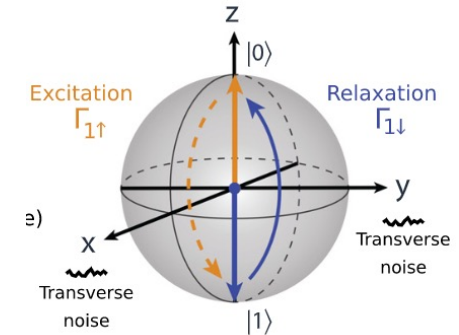
No variation

O... optical qubit, metastable lvl.
 HF... hyperfine qubit, ground states
 * ... in the absence of collisions

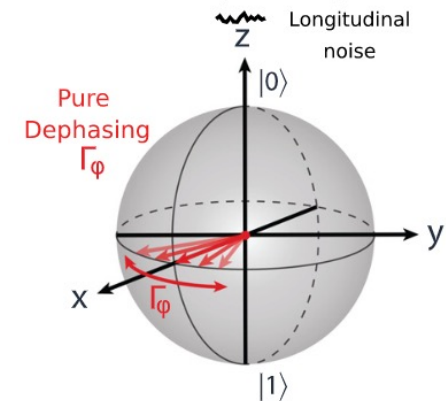
Coherence times



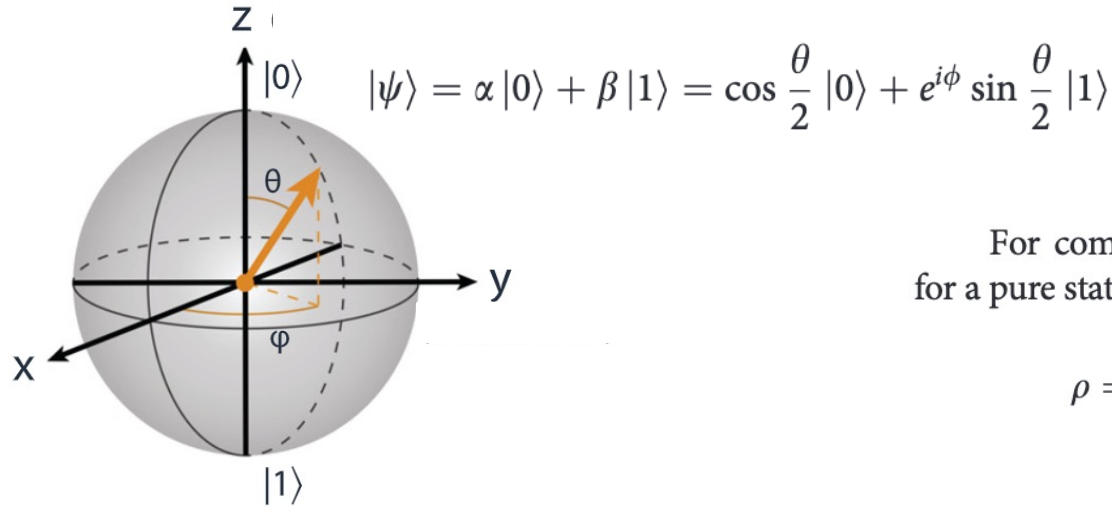
(b) Longitudinal relaxation



(c) Pure dephasing



Decoherence processes



$$1/T_2 = 1/T_\phi + 1/2T_1.$$

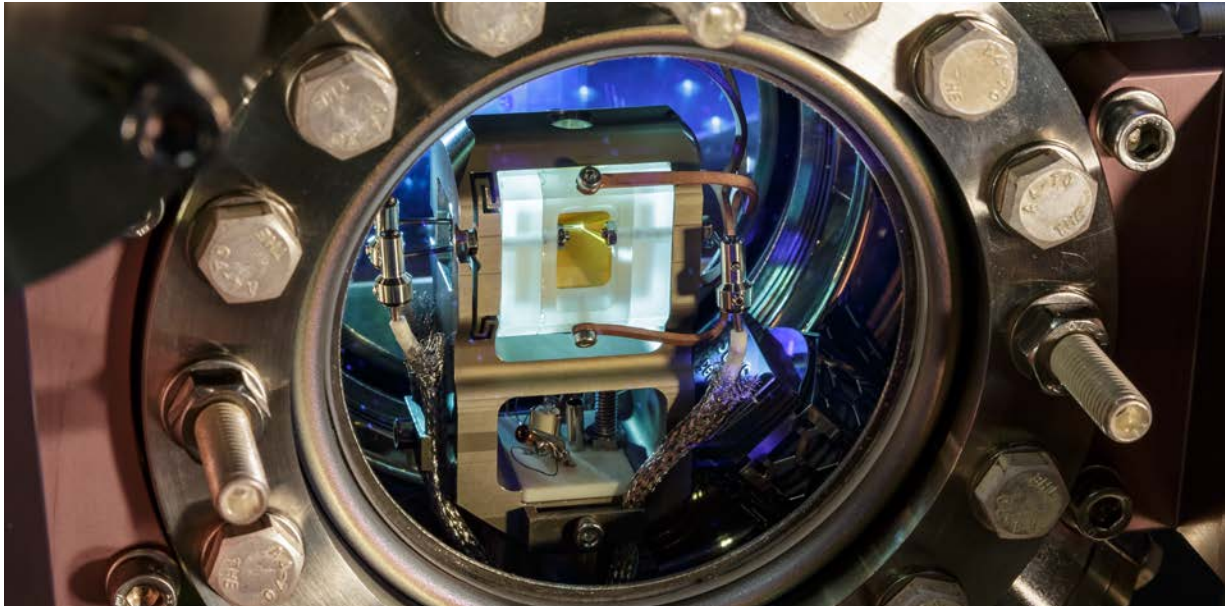
For completeness, we note that the density matrix $\rho = |\psi\rangle\langle\psi|$ for a pure state $|\psi\rangle$ is equivalently

$$\rho = \frac{1}{2}(I + \vec{a} \cdot \vec{\sigma}) = \frac{1}{2} \begin{pmatrix} 1 + \cos\theta & e^{-i\phi}\sin\theta \\ e^{i\phi}\sin\theta & 1 - \cos\theta \end{pmatrix} \quad (37)$$

$$= \begin{pmatrix} \cos^2\frac{\theta}{2} & e^{-i\phi}\cos\frac{\theta}{2}\sin\frac{\theta}{2} \\ e^{i\phi}\cos\frac{\theta}{2}\sin\frac{\theta}{2} & \sin^2\frac{\theta}{2} \end{pmatrix} \quad (38)$$

$$= \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix} \quad (39)$$

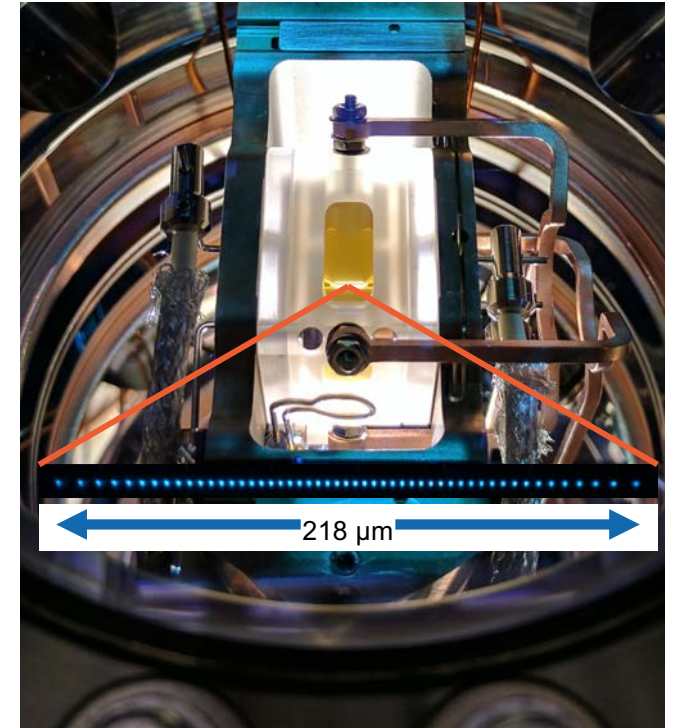
$$\rho_{\text{BR}} = \begin{pmatrix} 1 + (|\alpha|^2 - |\beta|^2)e^{-\Gamma_1 t} & \alpha\beta^* e^{i\delta\omega t} e^{-\Gamma_2 t} \\ \alpha^*\beta e^{-i\delta\omega t} e^{-\Gamma_2 t} & |\beta|^2 e^{-\Gamma_1 t} \end{pmatrix}.$$



IQOQI Innsbruck, Austria

Ion trap qubits

A workhorse for Quantum Information



University of Sydney,
Australia

Quantum jumps (1952)

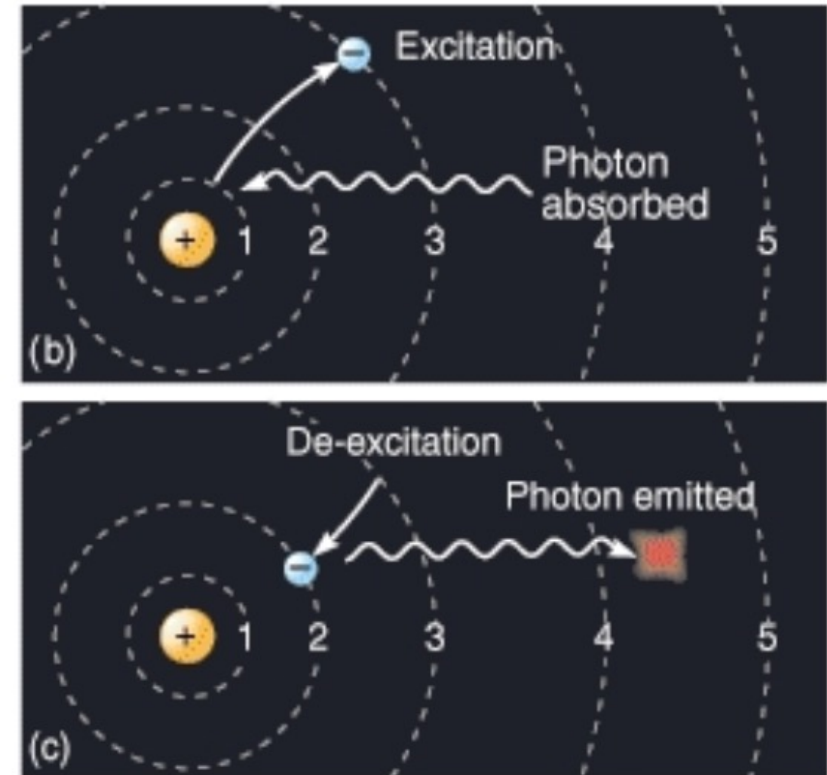
Image: <https://www.aps.org/>



“[...] we never experiment with just one electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences [...]”

Schrödinger, E. - Are There Quantum Jumps? Part II.

The British Journal for the Philosophy of Science **3**, 233–242 (1952).



Copyright 1998 by John Wiley and Sons, Inc. All rights reserved.

Thought-experiments become reality (1975/1980)

→ Cooling of atoms with light

D. J. Wineland and H. Dehmelt, *Bull. Am. Phys. Soc.* **20**, 637 (1975)

T. W. Hänsch and A. L. Schawlow, [Opt. Commun.](#) **13**, 68 (1975)

More:

physics.aps.org/story/v21/st11

VOLUME 40, NUMBER 25

PHYSICAL REVIEW LETTERS

19 JUNE 1978

Radiation-Pressure Cooling of Bound Resonant Absorbers

D. J. Wineland, R. E. Drullinger, and F. L. Walls
Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80303
(Received 26 April 1978)

PHYSICAL REVIEW A

VOLUME 20, NUMBER 4

OCTOBER 1979

Laser cooling of atoms

D. J. Wineland
Frequency and Time Standards Group, National Bureau of Standards, Boulder, Colorado 80303

Wayne M. Itano*
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 16 May 1979)

PHYSICAL REVIEW A

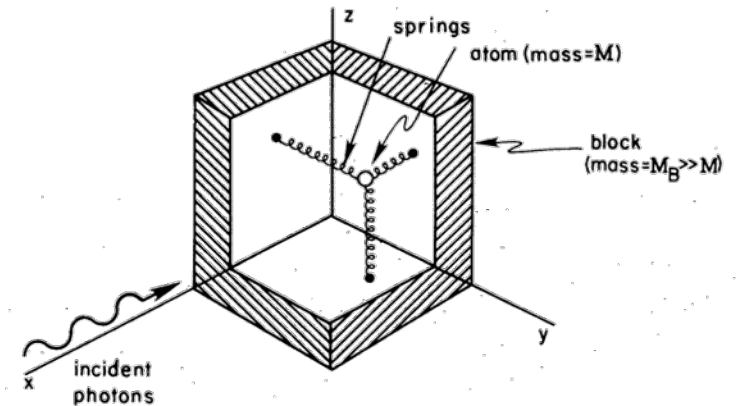
VOLUME 22, NUMBER 3

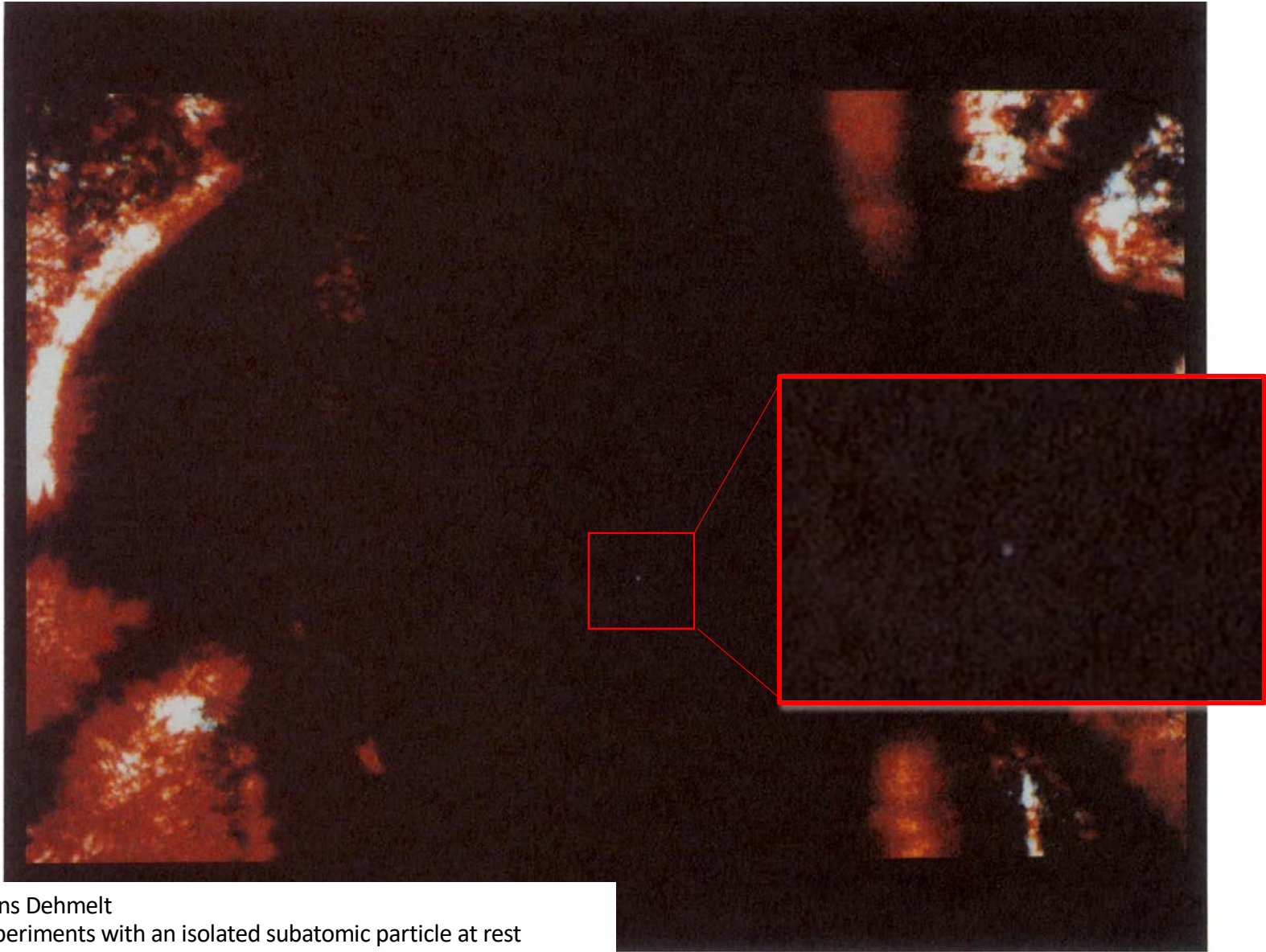
SEPTEMBER 1980

Localized visible Ba^+ mono-ion oscillator

W. Neuhauser, M. Hohenstatt, and P. E. Toschek
Institut für Angewandte Physik I der Universität Heidelberg, D-69 Heidelberg, Federal Republic of Germany

H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 11 September 1979)





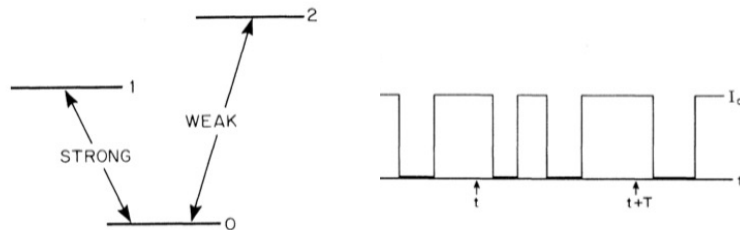
Hans Dehmelt
Experiments with an isolated subatomic particle at rest
Rev. Mod. Phys. **62**, 525 (1990)

Quantum jumps (1980s)

Single ions

PRA 22, 1137 (1980)

Phys. Lett. 82A, 75 (1981)



VOLUME 54, NUMBER 10

PHYSICAL REVIEW LETTERS

11 MARCH 1985

Possibility of Direct Observation of Quantum Jumps

Richard J. Cook

Department of Physics, Air Force Institute of Technology, Wright-Patterson Air Force Base, Dayton, Ohio 45433

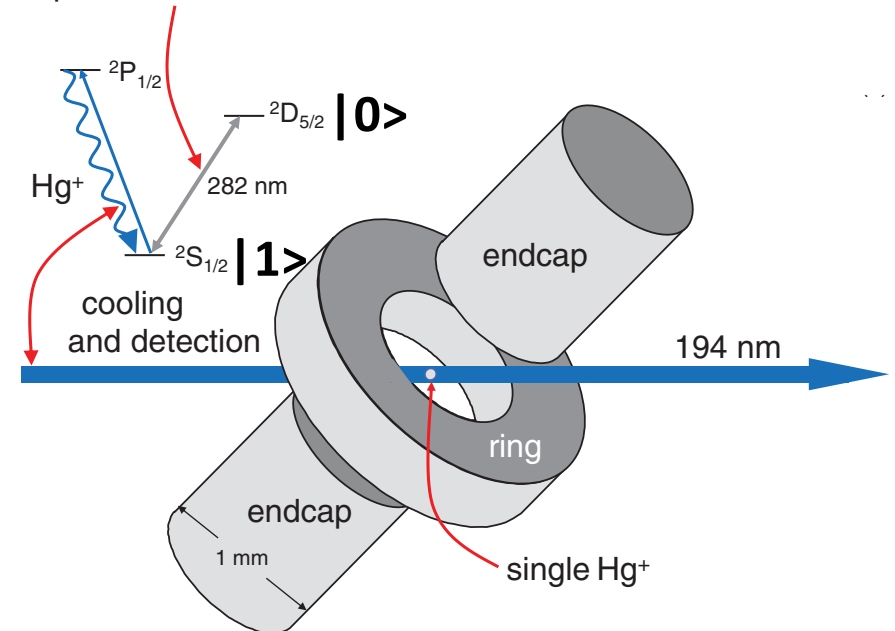
and

H. J. Kimble

Department of Physics, University of Texas at Austin, Austin, Texas 78712

(Received 3 December 1984)

"optical clock" transition



Quantum jumps

Dehmelt

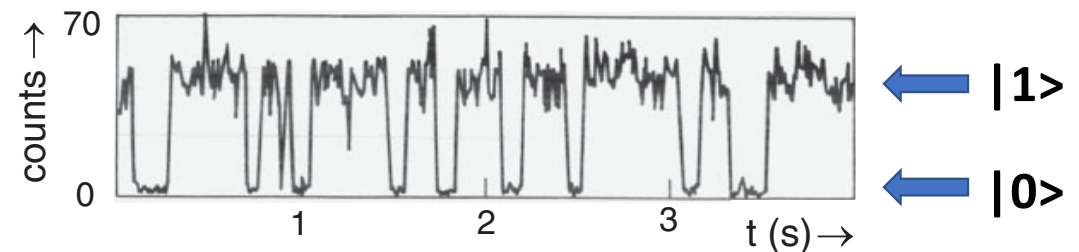
PRL 56, 2797 (1986)

Blatt, Toscheck

PRL 57, 1696 (1986)

Wineland

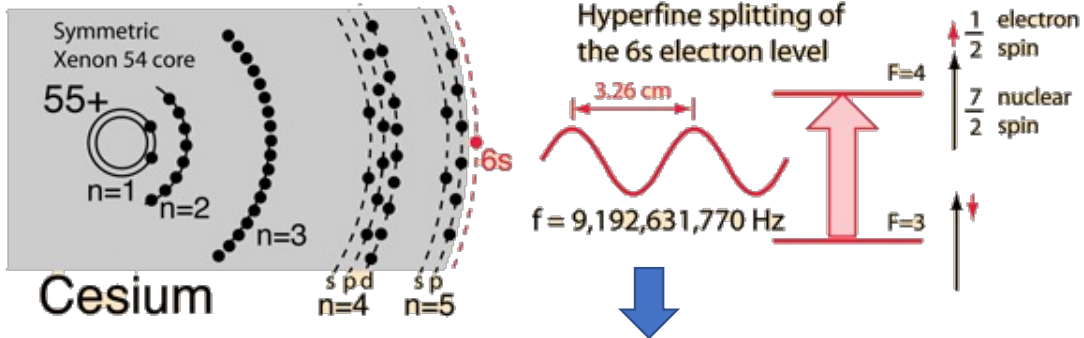
PRL 57, 1699 (1986)



D. Wineland *Rev. Mod. Phys.* **85**, 1103 (2013).

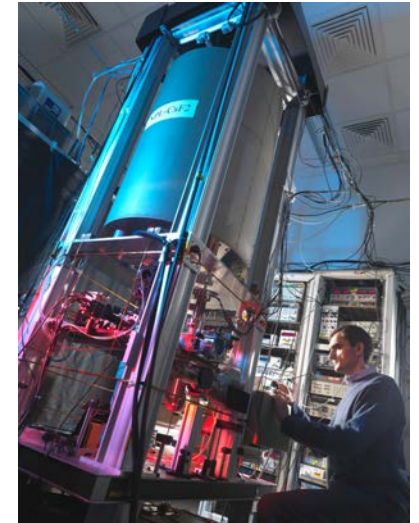
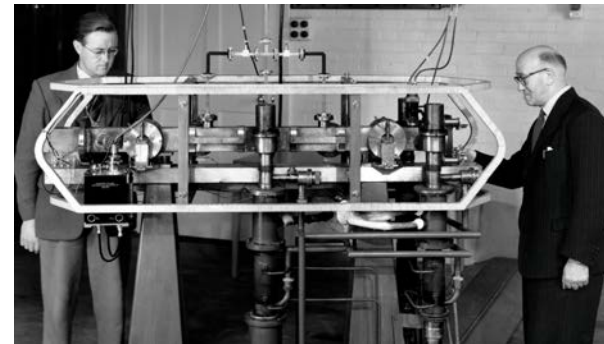
Time standards / clocks

<http://hyperphysics.phy-astr.gsu.edu>



1955

Images: NPL

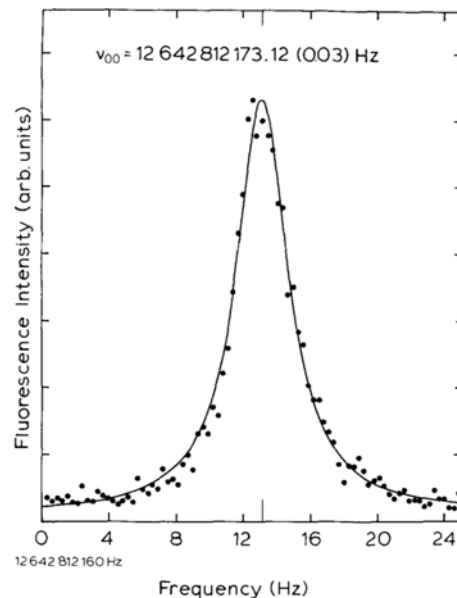


$^{171}\text{Yb}^+$

hyperfine levels

Rainer Blatt (1983)

Fisk, P. T. H (1997) @
NMI Lindfield
(most accurate clock in
the world for a few
weeks!)



Go up in Q
(linewidth/frequency)

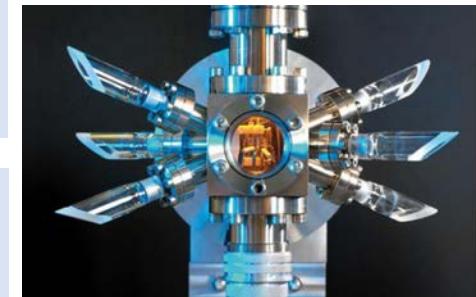
Optical atomic
clocks
GHz $\rightarrow$ THz

Reduce motion

$^{171}\text{Yb}^+$ F-state
(3 year lifetime)

Accuracy: **3.0×10^{-18}**
PTB Germany
PRL **116**, 063001 (2016)

Accuracy: **9.4×10^{-19}**
NIST USA
PRL **123**, 033201 (2019).



2018 NPL UK (Cs atoms)

5.4×10^{-13} at 1 s
 4.0×10^{-16} at 20d

Which elements are good for storing quantum bits?

PERIODIC TABLE
Atomic Properties of the Elements

Physics Laboratory NIST Standard Reference Data Program
physics.nist.gov www.nist.gov www.nist.gov/srd

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum c 299 792 458 m s $^{-1}$ (exact)
Planck constant h 6.626 070 15 $\times 10^{-34}$ J s ($h = h/2\pi$)
elementary charge e 1.602 176 634 $\times 10^{-19}$ C
electron mass m_e 9.109 383 56 $\times 10^{-31}$ kg
 $m_e c^2$ 0.511 0 MeV
 m_p 1.672 6 $\times 10^{-27}$ kg
 $m_p c^2$ 938.272 088 MeV
proton mass m_p 1.672 6 $\times 10^{-27}$ kg
fine-structure constant α 1/137.036
Rydberg constant R_∞ 10 973 731.568 16 m $^{-1}$
 $R_\infty c$ 3.289 84 $\times 10^{15}$ Hz
 $R_\infty h c$ 13.605 698 eV
Boltzmann constant k 1.380 658 $\times 10^{-23}$ J K $^{-1}$

Atom
Closed shells + Nucleus

Ion
Closed shells + Nucleus

Photoionization
continuum $E_0 = 6.11$ eV
 < 389.92 nm
4s4p 1P_1
4s 2 1S_0 Ca I
422.79 nm

Legend:
Solids (blue)
Liquids (green)
Gases (pink)
Artificially Prepared (yellow)

For a description of the atomic data, visit physics.nist.gov/atomic

March 1999

Singly-charged ions appropriate for quantum information processing

Physics Laboratory Standard Reference Data Program physics.nist.gov www.nist.gov www.nist.gov/srd U.S. DEPARTMENT OF COMMERCE Technology Administration National Institute of Standards and Technology															
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs speed of light in vacuum c 299 792 458 m s^{-1} (exact) Planck constant h 6.626 070 15 $\times 10^{-34}$ J s (exact) ($\hbar = h/2\pi$) elementary charge e 1.602 176 634 $\times 10^{-19}$ C electron mass m_e 9.109 383 701 $\times 10^{-31}$ kg proton mass m_p 1.672 621 923 6 $\times 10^{-27}$ kg fine-structure constant α 1/137.035 999 074 Rydberg constant R_∞ 10 973 731.762 53 m^{-1} Boltzmann constant k 1.380 658 $\times 10^{-23}$ J K^{-1}															
IIA 3 $^2\text{S}_{1/2}$ Li 4 $^2\text{S}_{1/2}$ Be 11 $^2\text{S}_{1/2}$ Na 12 $^2\text{S}_{1/2}$ Mg 19 $^2\text{S}_{1/2}$ K 20 $^2\text{S}_{1/2}$ Ca 37 $^2\text{S}_{1/2}$ Rb 38 $^2\text{S}_{1/2}$ Sr 55 $^2\text{S}_{1/2}$ Cs 56 $^2\text{S}_{1/2}$ Ba 87 $^2\text{S}_{1/2}$ Fr 88 $^2\text{S}_{1/2}$ Ra															
IIIB 5 $^2\text{P}_{1/2}$ B 13 $^2\text{P}_{1/2}$ Al 21 $^2\text{D}_{3/2}$ Sc 39 $^2\text{D}_{3/2}$ Y 57 $^2\text{F}_{7/2}$ La 71 $^2\text{F}_{7/2}$ Pr 89 $^2\text{F}_{7/2}$ Ac															
IVB 6 $^3\text{P}_0$ C 14 $^3\text{P}_0$ Si 22 $^3\text{F}_2$ Ti 40 $^3\text{F}_2$ Zr 58 $^3\text{F}_4$ Hf 72 $^3\text{F}_4$ Th 90 $^3\text{F}_4$ U															
VB 7 $^4\text{S}_{3/2}$ N 15 $^4\text{S}_{3/2}$ P 23 $^4\text{F}_{3/2}$ V 41 $^4\text{D}_{3/2}$ Nb 59 $^4\text{F}_{3/2}$ Ta 73 $^4\text{F}_{3/2}$ Ta 91 $^4\text{F}_{3/2}$ Ta															
VIB 8 $^3\text{P}_1$ O 16 $^3\text{P}_1$ S 24 $^3\text{F}_2$ Cr 42 $^3\text{F}_2$ Mo 60 $^3\text{F}_2$ Zr 74 $^3\text{F}_2$ Zr 92 $^3\text{F}_2$ Zr															
VII B 9 $^2\text{P}_{3/2}$ F 17 $^2\text{P}_{3/2}$ Cl 25 $^2\text{D}_{5/2}$ Mn 43 $^2\text{D}_{5/2}$ Tc 61 $^2\text{D}_{5/2}$ Yb 75 $^2\text{D}_{5/2}$ Yb 93 $^2\text{D}_{5/2}$ Yb															
VIII 2 $^1\text{S}_0$ He 10 $^1\text{S}_0$ Ne 18 $^1\text{S}_0$ Ar 36 $^1\text{S}_0$ Kr 54 $^1\text{S}_0$ Xe 86 $^1\text{S}_0$ Rn															
IB 29 $^1\text{S}_{1/2}$ Cu 47 $^1\text{S}_{1/2}$ Ag 63 $^1\text{S}_{1/2}$ Au 79 $^1\text{S}_{1/2}$ Au 95 $^1\text{S}_{1/2}$ Au															
IIB 30 $^1\text{S}_{1/2}$ Zn 48 $^1\text{S}_{1/2}$ Cd 64 $^1\text{S}_{1/2}$ Hg 80 $^1\text{S}_{1/2}$ Hg 96 $^1\text{S}_{1/2}$ Hg															
IIIB 31 $^2\text{P}_{1/2}$ Ga 49 $^2\text{P}_{1/2}$ In 65 $^2\text{P}_{1/2}$ Tl 81 $^2\text{P}_{1/2}$ Tl 97 $^2\text{P}_{1/2}$ Tl															
IVB 32 $^3\text{P}_0$ Ge 50 $^3\text{P}_0$ Sn 66 $^3\text{P}_0$ Pb 82 $^3\text{P}_0$ Pb 98 $^3\text{P}_0$ Pb															
VB 33 $^4\text{S}_{3/2}$ As 51 $^4\text{S}_{3/2}$ Sb 67 $^4\text{S}_{3/2}$ Bi 83 $^4\text{S}_{3/2}$ Bi 99 $^4\text{S}_{3/2}$ Bi															
VIB 34 $^3\text{P}_1$ Se 52 $^3\text{P}_1$ Te 68 $^3\text{P}_1$ Po 84 $^3\text{P}_1$ Po 100 $^3\text{P}_1$ Po															
VII B 35 $^2\text{P}_{3/2}$ Br 53 $^2\text{P}_{3/2}$ I 69 $^2\text{P}_{3/2}$ At 85 $^2\text{P}_{3/2}$ At 101 $^2\text{P}_{3/2}$ At															
VIII 36 $^1\text{S}_0$ Kr 54 $^1\text{S}_0$ Xe 86 $^1\text{S}_0$ Rn 102 $^1\text{S}_0$ No 108 $^1\text{S}_0$ Lr															

Atom

Closed shells + Nucleus

Photo ionization

Closed shells + Nucleus

Ion

58 $^1\text{G}_0$ Ce

Cerium

140.116

[Xe]4f5d6s 2

5.5387

Ground-state Configuration

Ionization Energy (eV)

67 $^4\text{I}_{9/2}$ Ho

Erbium

167.26

[Xe]4f 14 6s 2

6.0215

Ground-state Configuration

Ionization Energy (eV)

68 $^3\text{H}_6$ Er

Erbium

167.26

[Xe]4f 14 6s 2

6.1077

Ground-state Configuration

Ionization Energy (eV)

69 $^2\text{F}_{7/2}$ Tm

Thulium

168.93421

[Xe]4f 14 6s 2

6.1843

Ground-state Configuration

Ionization Energy (eV)

70 $^2\text{F}_{7/2}$ Yb

Ytterbium

173.04

[Xe]4f 14 6s 2

6.42

Ground-state Configuration

Ionization Energy (eV)

71 $^2\text{D}_{3/2}$ Lu

Lutetium

174.967

[Xe]4f 14 5d6s 2

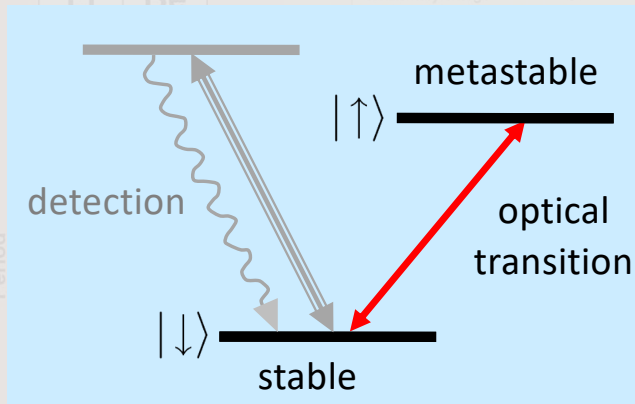
6.4259

Ground-state Configuration

Ionization Energy (eV)

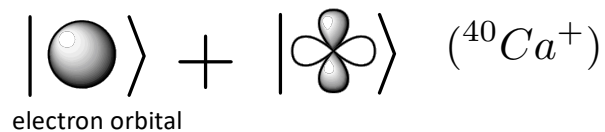
Types of trapped ion quantum bits

Ions with optical transition to metastable level: $^{40}\text{Ca}^+$, $^{88}\text{Sr}^+$, $^{172}\text{Yb}^+$



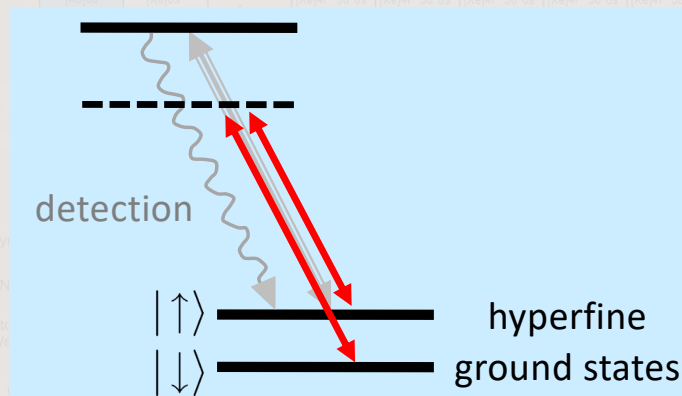
“optical qubit”

qubit manipulation requires
ultrastable laser



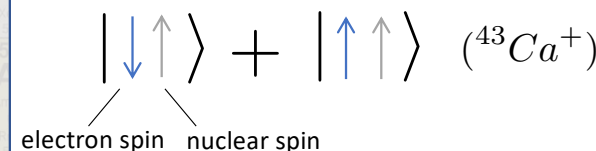
$$\Psi = \alpha|\downarrow\rangle + \beta|\uparrow\rangle$$

Ions with hyperfine structure: $^9\text{Be}^+$, $^{25}\text{Mg}^+$, $^{43}\text{Ca}^+$, $^{111}\text{Cd}^+$, $^{171}\text{Yb}^+$...

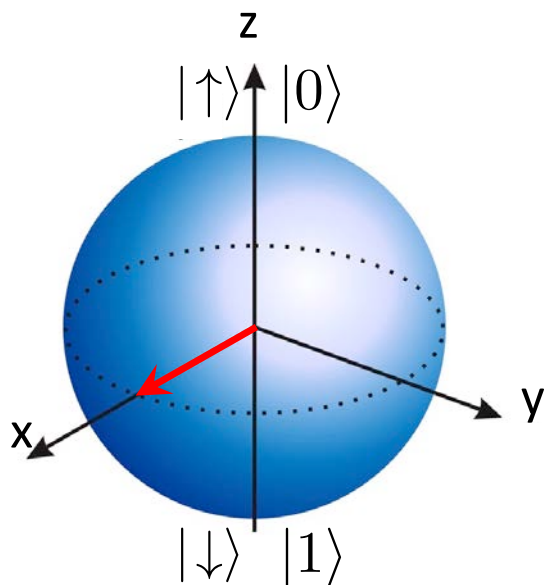


“hyperfine qubit”

qubit manipulation with
microwaves or lasers (Raman transitions)



Encoding and reading out a qubit in an ion



$$|\Psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$

$$p_{|\uparrow\rangle} = |\alpha|^2$$


$$p_{|\downarrow\rangle} = |\beta|^2$$


$$\tau \approx 7 \text{ ns} \quad \text{P}_{1/2}$$

“Electron shelving”
Dehmelt, H. G. (1982).

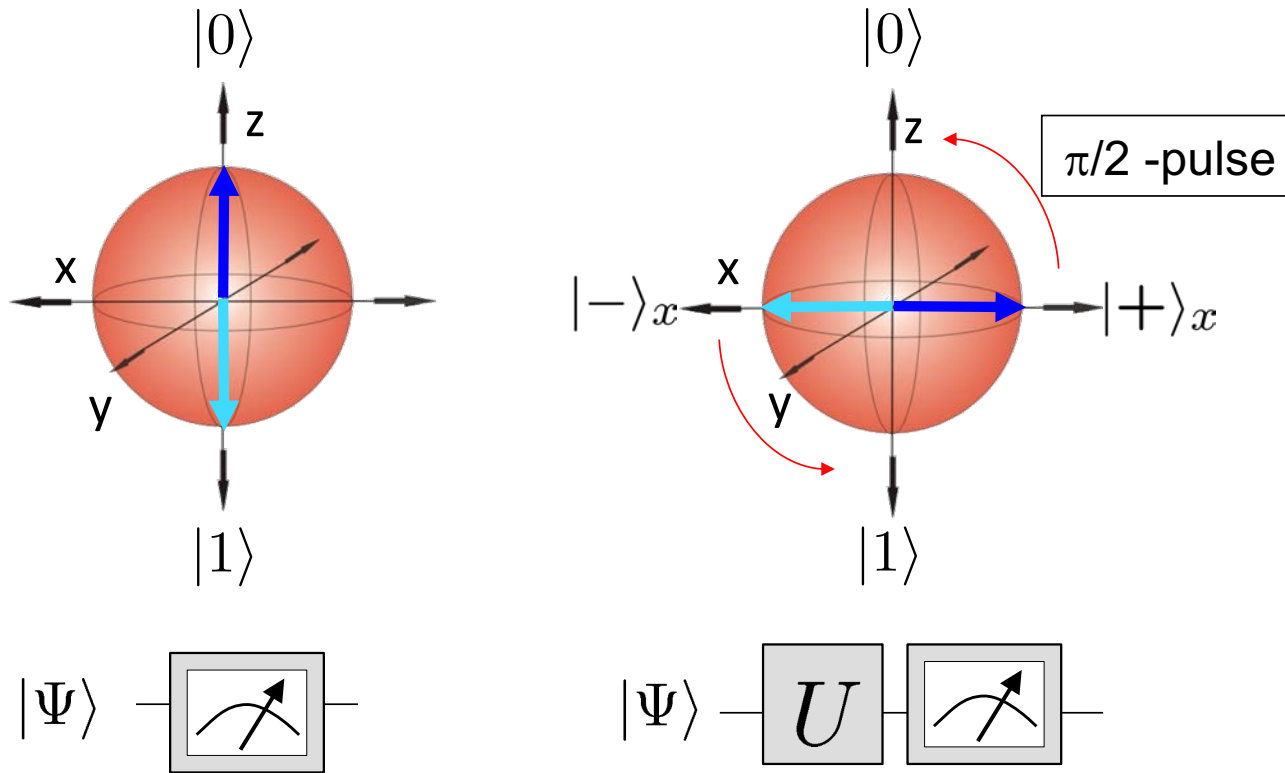
$$\tau \approx 1.1 \text{ s} \quad \text{D}_{5/2}$$



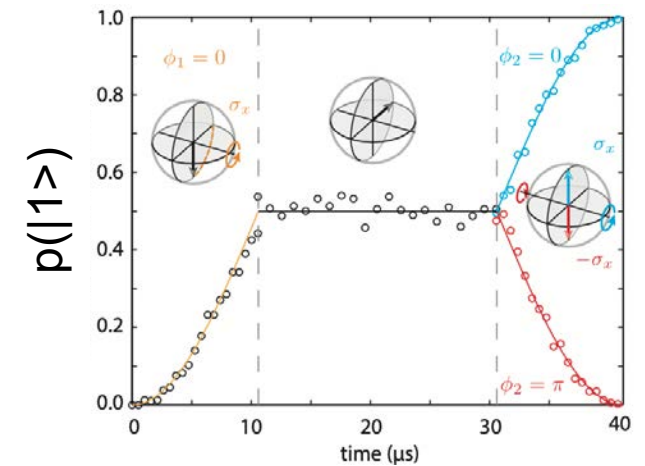
$$\text{S}_{1/2}$$



Measurement of expectation values / error bar

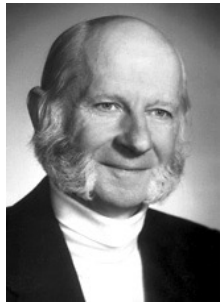


Quantum Projection Noise

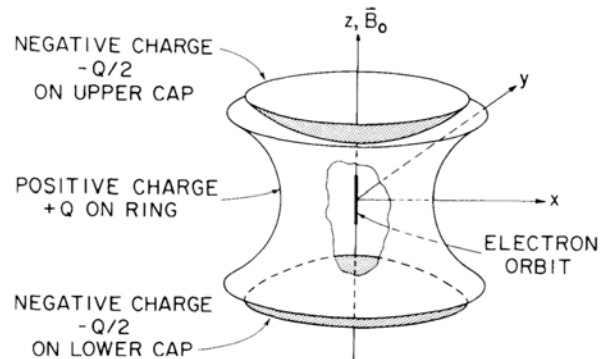


Trapping ions – two different types of ion traps

Penning trap



Hans Dehmelt

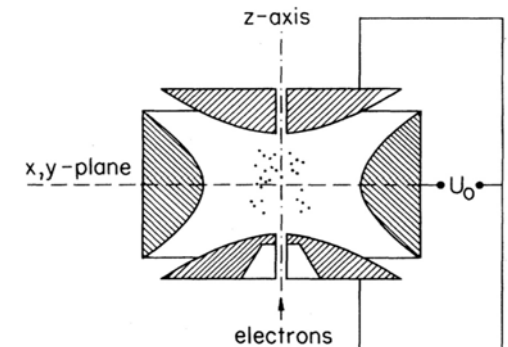


static fields

Paul trap



Wolfgang Paul



dynamic fields



Nobel Prize in Physics 1989

"for the development of the ion trap technique"

H. Dehmelt, Rev. Mod. Phys. **62**, 525 (1990).

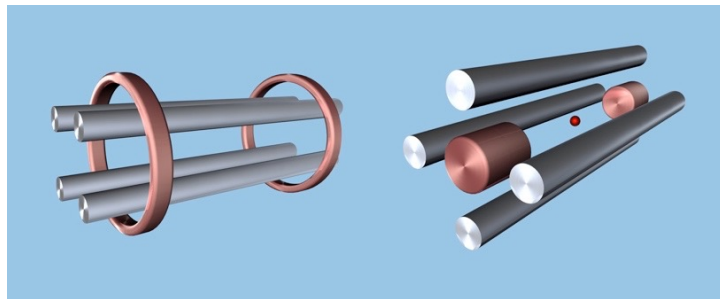
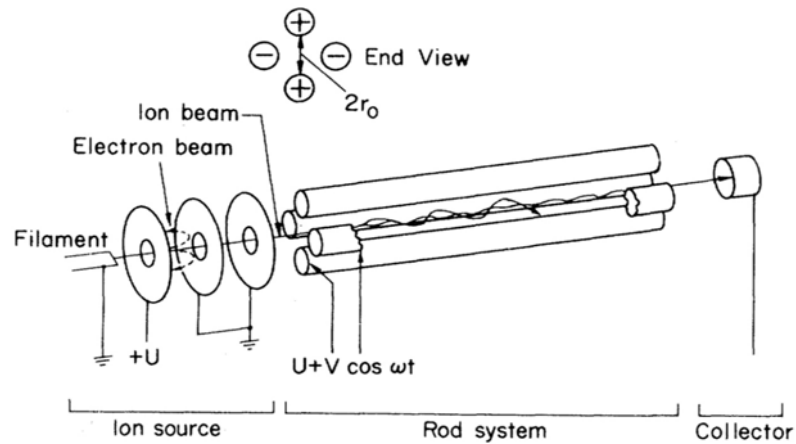
W. Paul, Rev. Mod. Phys. **62**, 531–540 (1990).

Paul traps over the years

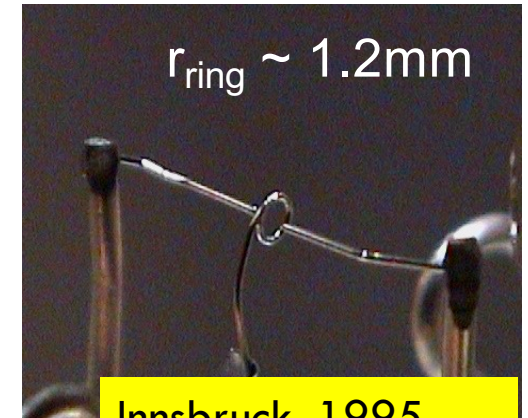
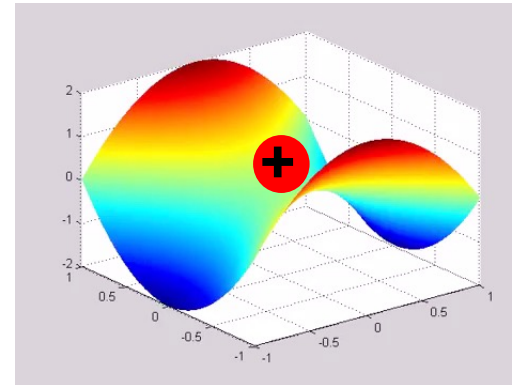
Ein neues Massenspektrometer ohne Magnetfeld

Von Wolfgang Paul und Helmut Steinwedel
Physikalisches Institut der Universität Bonn

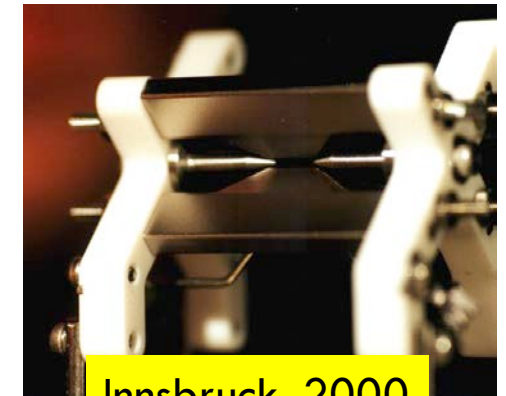
(Z. Naturforschg. 8a, 448—450 [1953]; eingegangen am 27. Mai 1953)



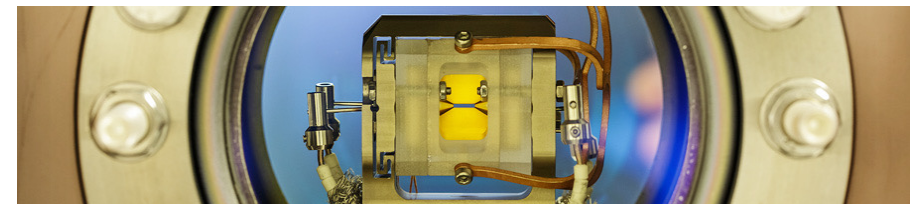
The University of Sydney



Innsbruck, 1995

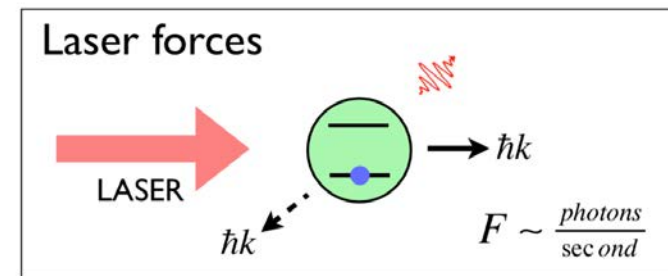
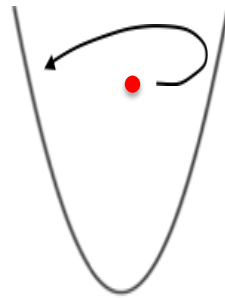
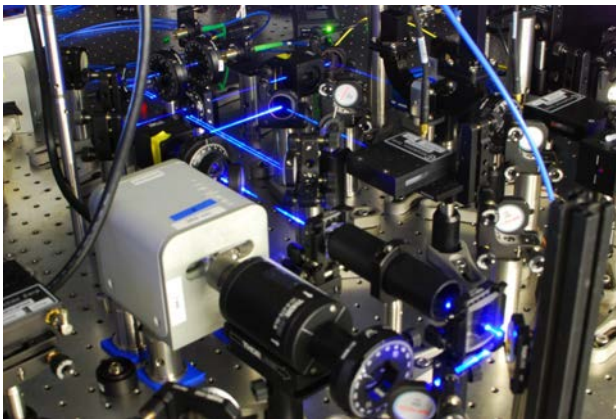
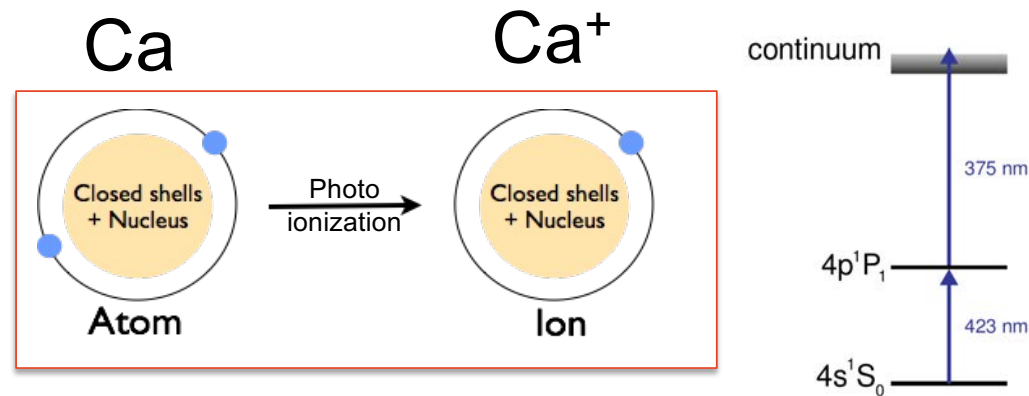
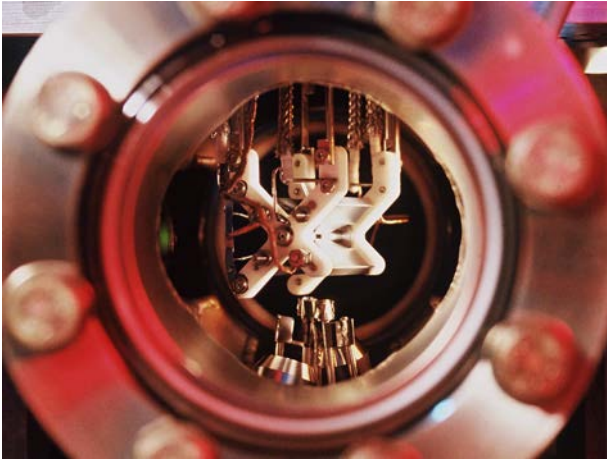


Innsbruck, 2000

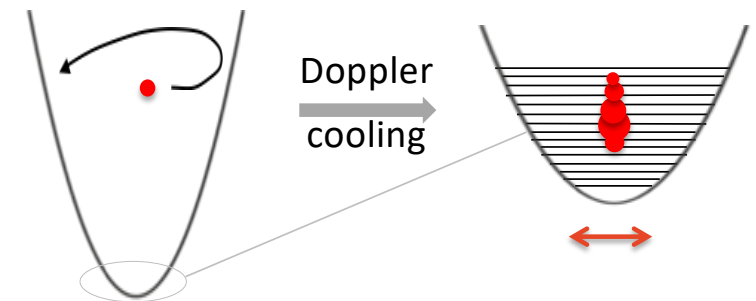


Innsbruck, 2012

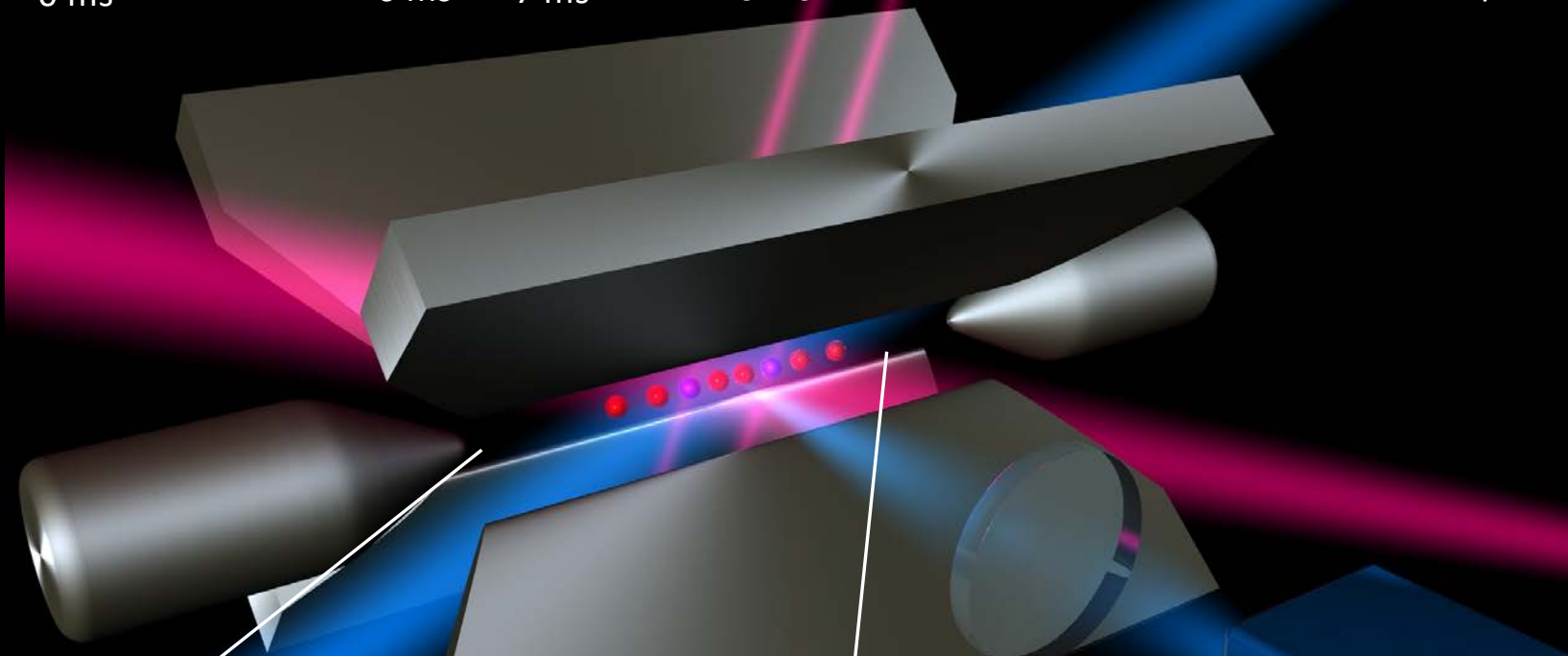
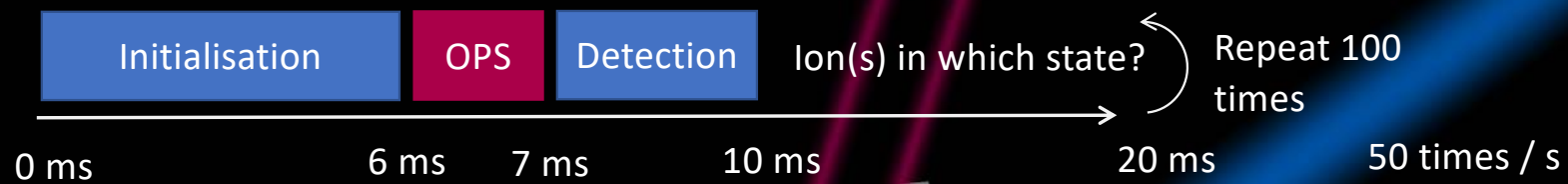
Ion loading and laser cooling

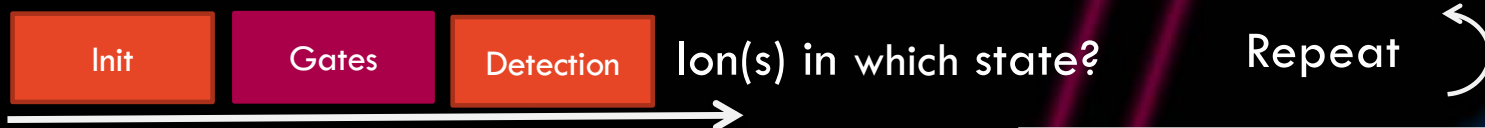


Doppler cooling

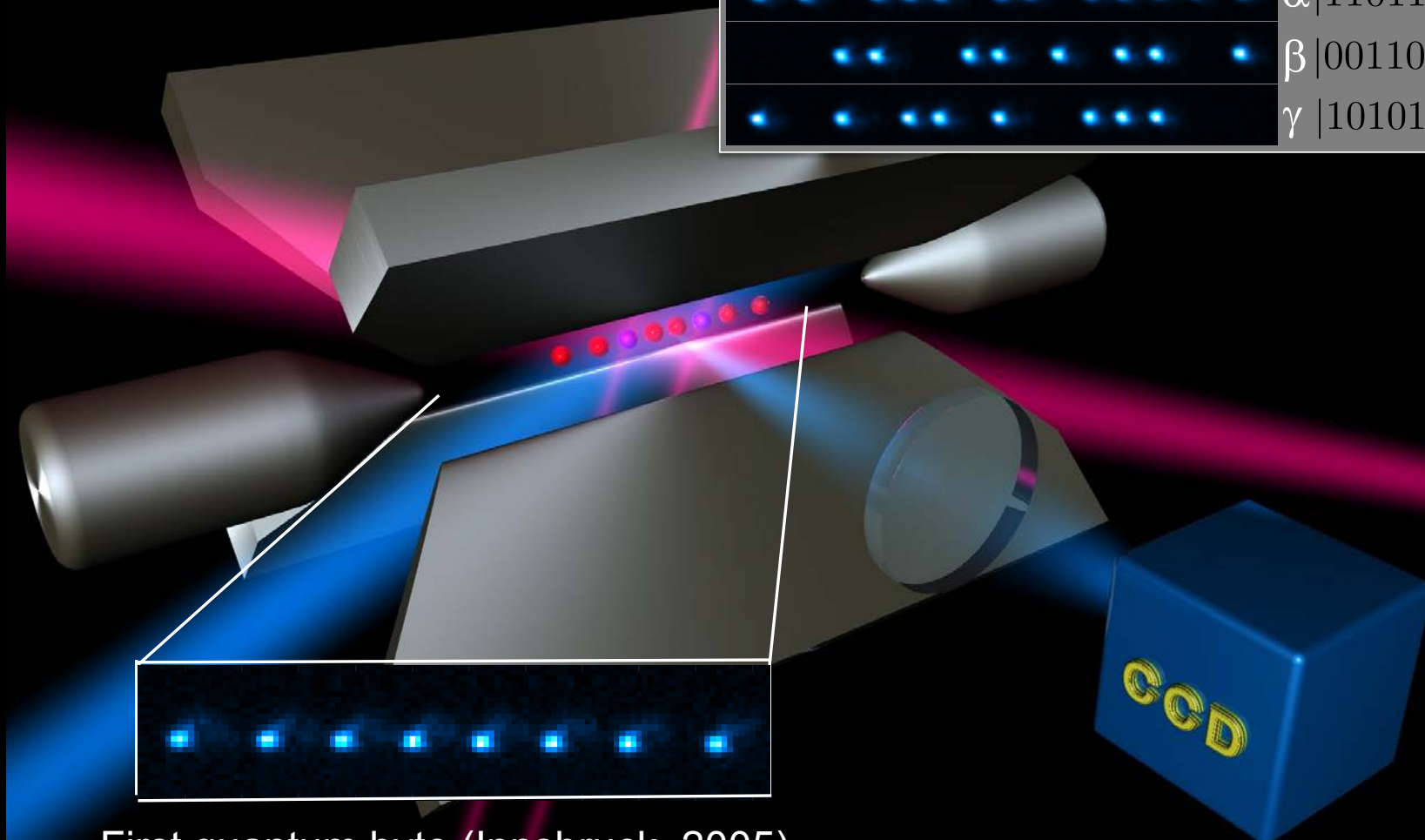


Wineland, D. J. & Itano, W. M. - Laser cooling of atoms. *Physical Review A* **20**, 1521–1540 (1979).





	$\alpha 110111011011111\rangle$
	$\beta 001100110101101\rangle$
	$\gamma 101011010011100\rangle$



First quantum byte (Innsbruck, 2005)

Rendering: Rainer Blatt

A photograph of a wooden table with a cup of coffee and a croissant. The cup is dark with a white lid and a handle, sitting on a matching saucer. The croissant is golden brown and flaky, resting on a small white plate. The text "Break" is overlaid in the center.

Break

Lecture continues at 11:45