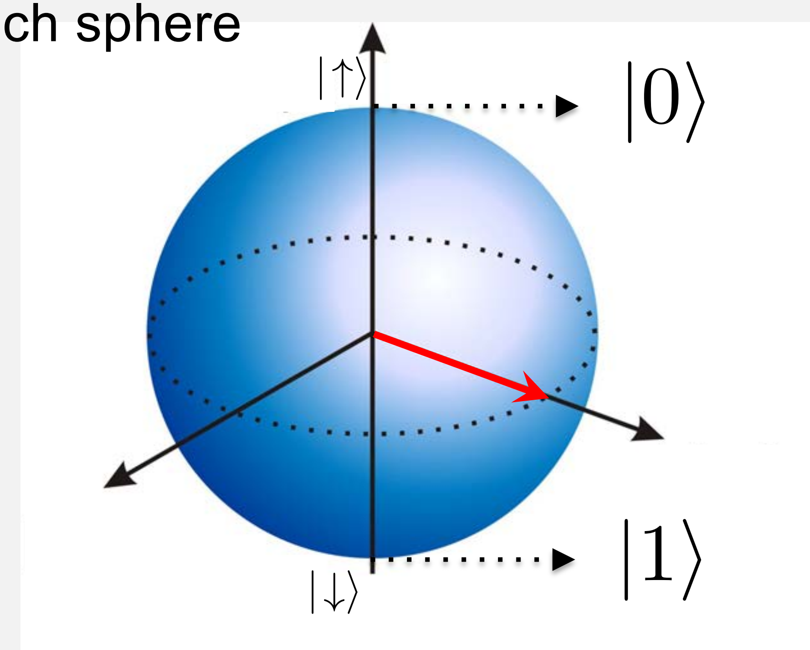
What is a quantum bit?

(Classical) *binary digit* **(bit)**

DRAM

„Qu(antum) bit“

Bloch sphere



$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

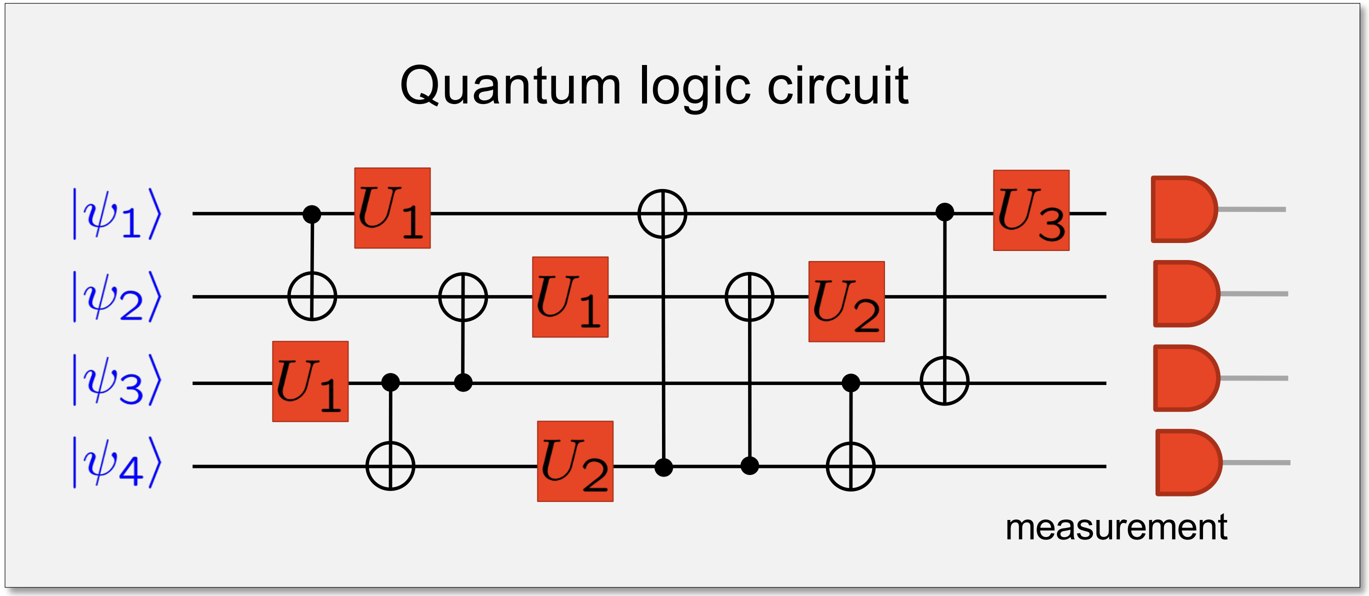
$$= \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$

NEW : Superposition & entanglement

Quantum information processing

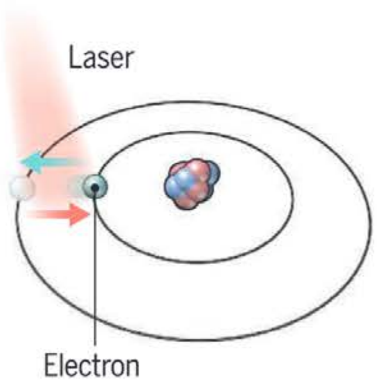
Classical vs. quantum information processing

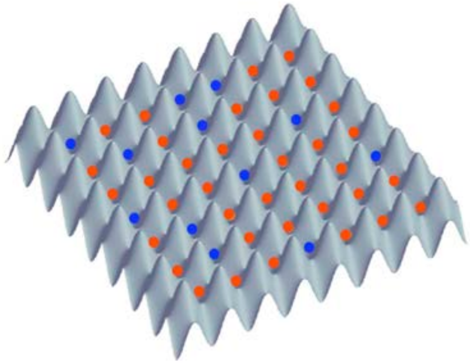
Quantum circuit

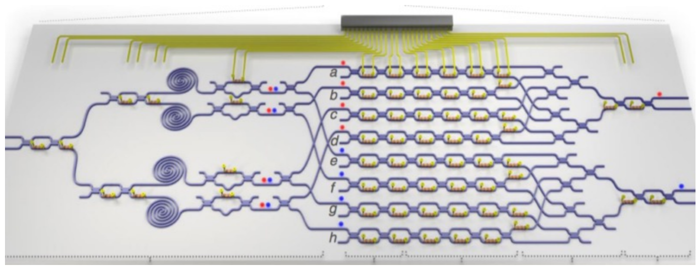


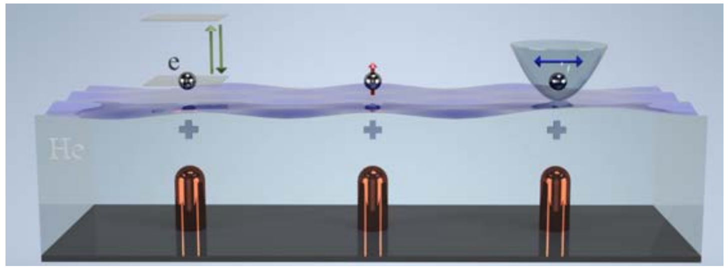
Types of qubits

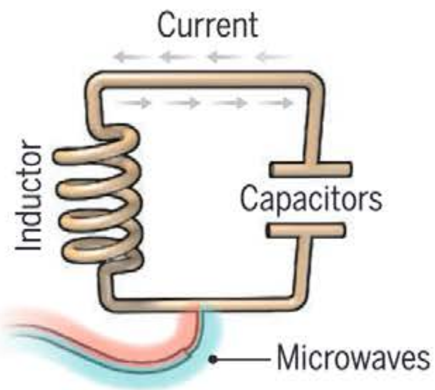
Modified from Science **354**, 1090 (2016)

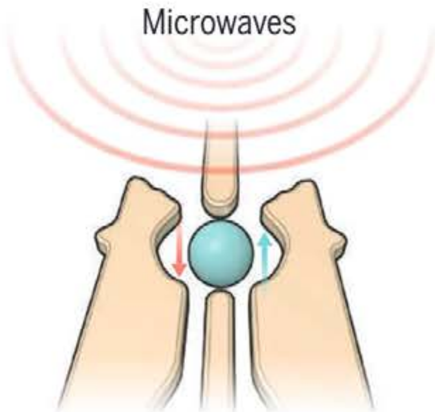


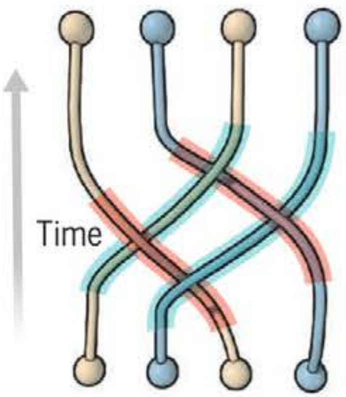


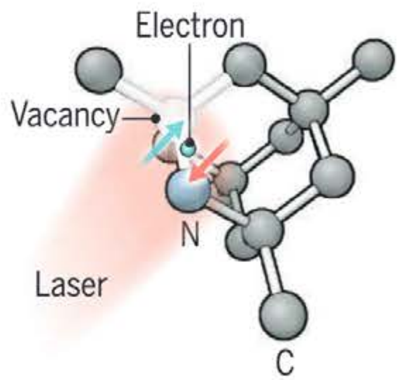












Comparison of key metrics (March 2022)

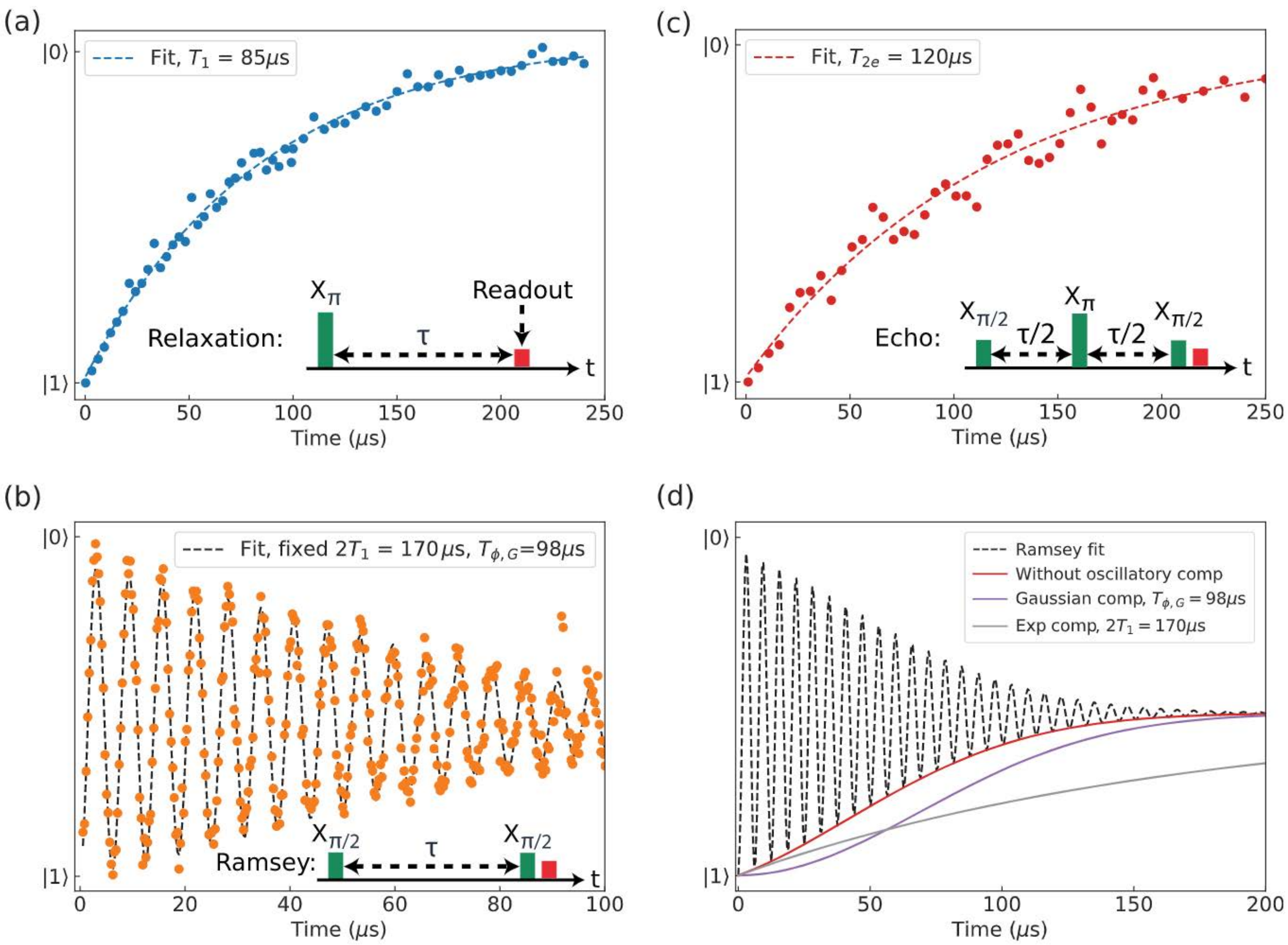
	Superconducting circuits	Trapped ions	
Relaxation time (T1)	15 – 100 µs	1 s (O)	infinite* (HF)
Phase coherence (T_2*)	20 – 100 µs	500 ms (O)	50 s (HF)
Single qubit gates	3x 10^{-3} – 10^{-4}	10^{-6} (fid: 99.9999%)	
Gate speed	15 ns	12 µs	
Two-qubit gates	98.1% - 99.3% (Google) 89.3% - 99.5%(IBM)	10^{-3} (fid: 99.9%)	
Gate speed	10 – 43 ns	1.6 µs / 30-100 µs	
Readout fidelity	93.1 – 99.3%	99+% (99.99%)	
scalability	Medium (size of C and dist)	Hard (complexity, optics+electonics)	
Comment	Inhomogeneous perf.	Homogeniety, but difficult to control	

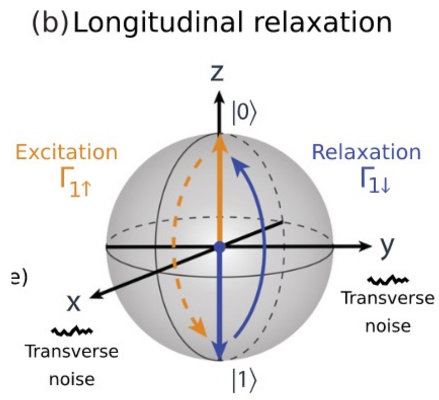
Coherence times in µs	T1			T2		
	min	max	avg	min	max	avg
IBM Q Kolkata 27	9.86	239.52	126.14	11.52	167.87	78.64
Google Sycamore	11	21	15	-	-	19

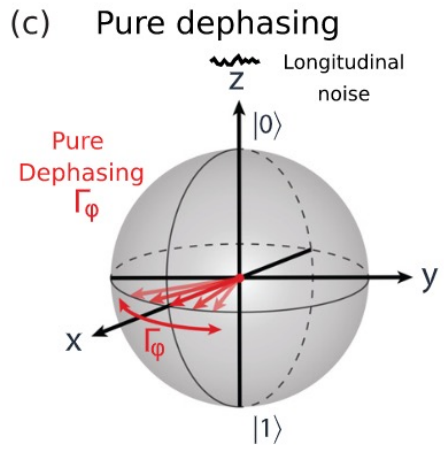
All ions are the same
No variation

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

Coherence times

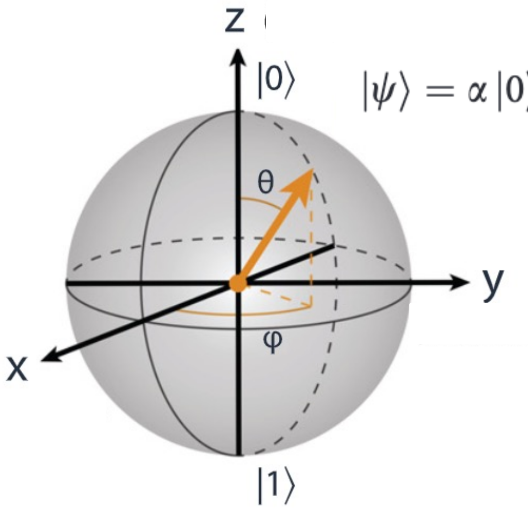






P. Krantz, et al., Applied Physics Reviews **6**, 021318 (2019).

Decoherence processes



$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\phi}\sin\frac{\theta}{2}\,|1\rangle$$

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

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

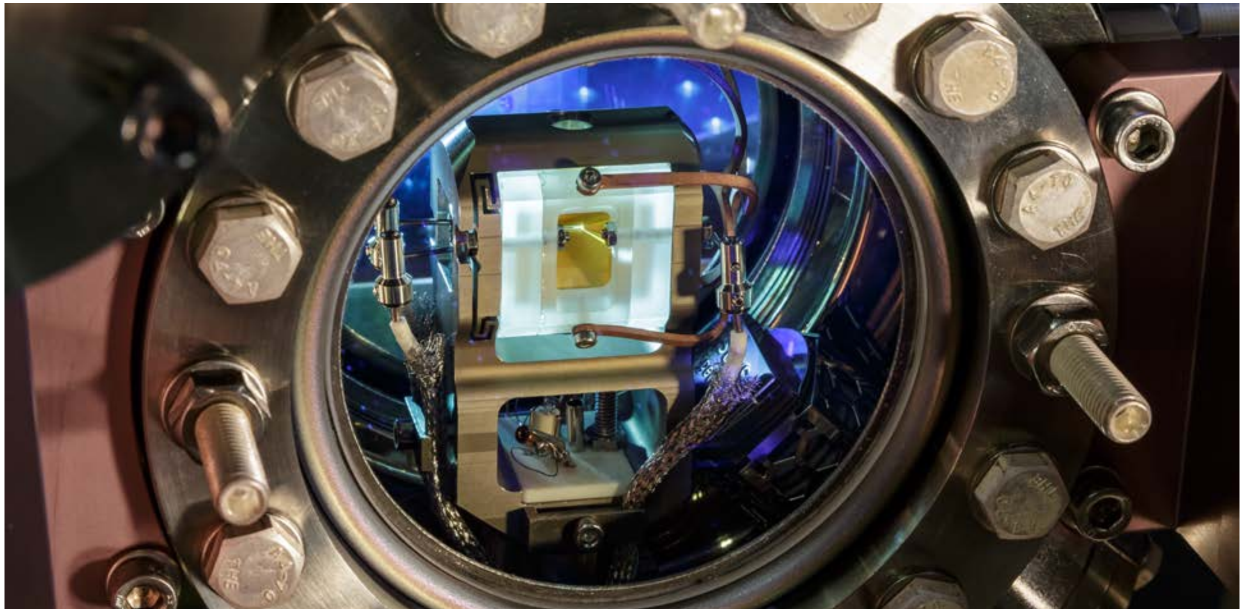
$$= \begin{pmatrix} \cos^2\frac{\theta}{2} & e^{-i\phi}\cos\frac{\theta}{2}\sin\frac{\theta}{2} \\ e^{i\phi}\cos\frac{\theta}{2}\sin\frac{\theta}{2} & \sin^2\frac{\theta}{2} \end{pmatrix} \quad (38)$$

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

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

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

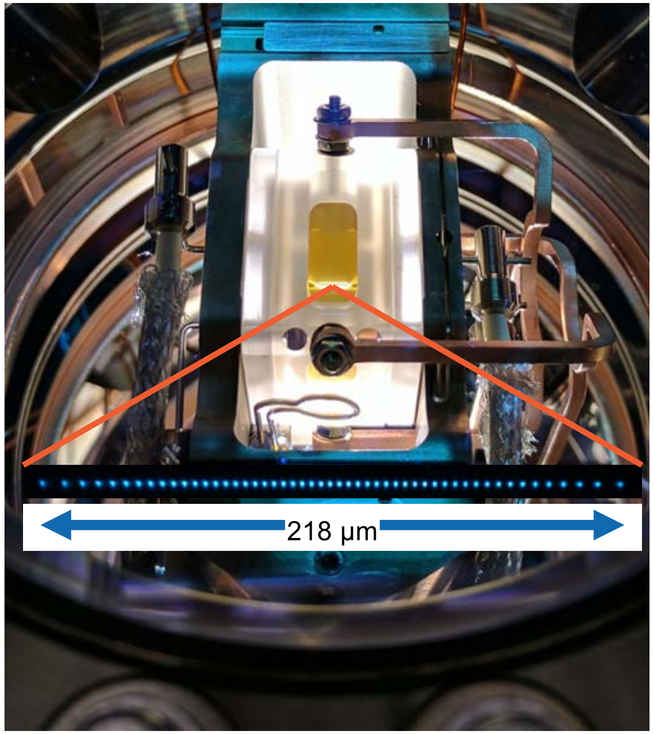
P. Krantz, et al., Applied Physics Reviews **6**, 021318 (2019).



IQOQI Innsbruck, Austria

Ion trap qubits

A workhorse for Quantum Information

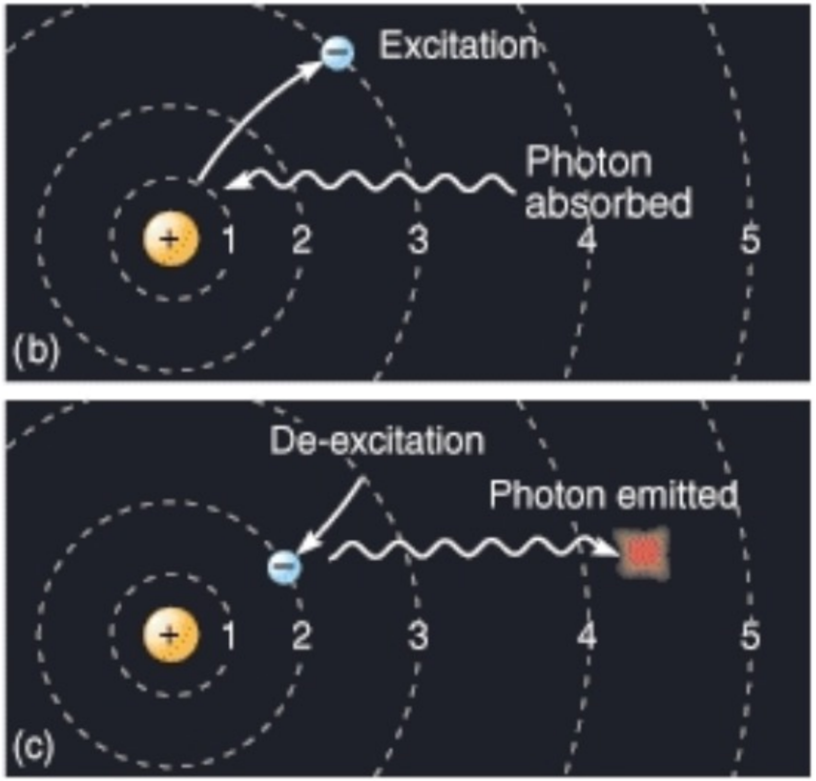


University of Sydney,
Australia

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).

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

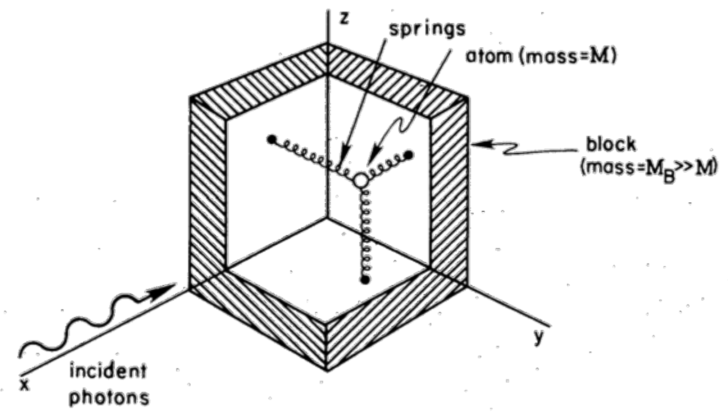
Wayne M. Itano*
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 16 May 1979)

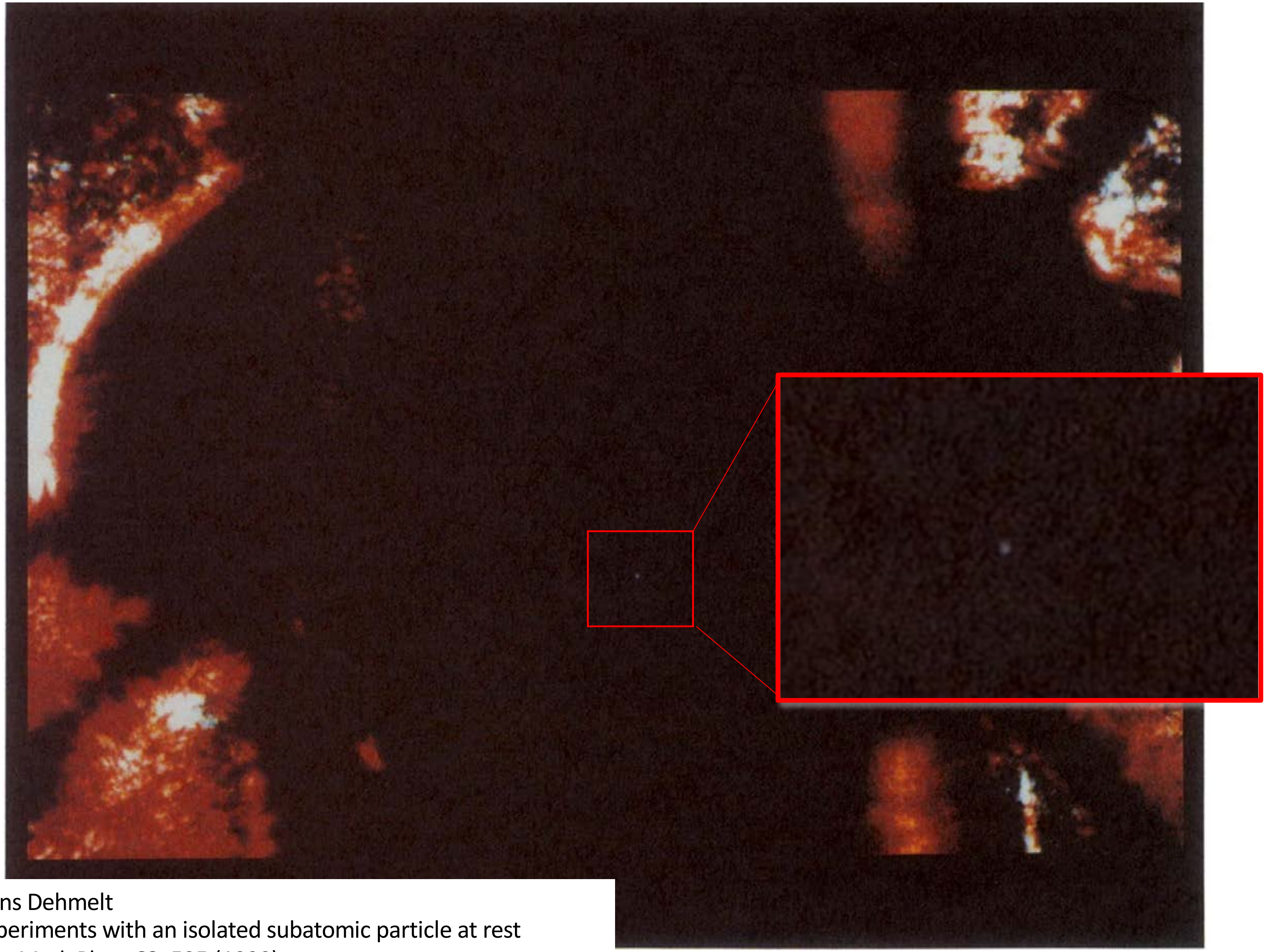
PHYSICAL REVIEW A VOLUME 22, NUMBER 3 SEPTEMBER 1980

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)





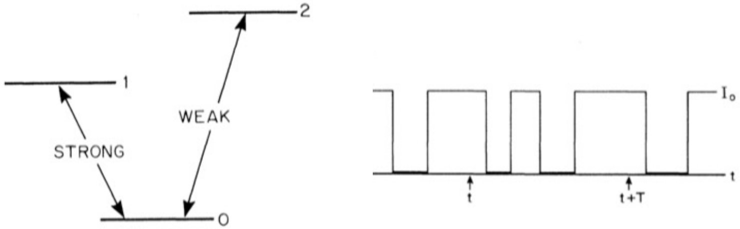
Hans Dehmelt
Experiments with an isolated subatomic particle at rest
Rev. Mod. Phys. **62**, 525 (1990)

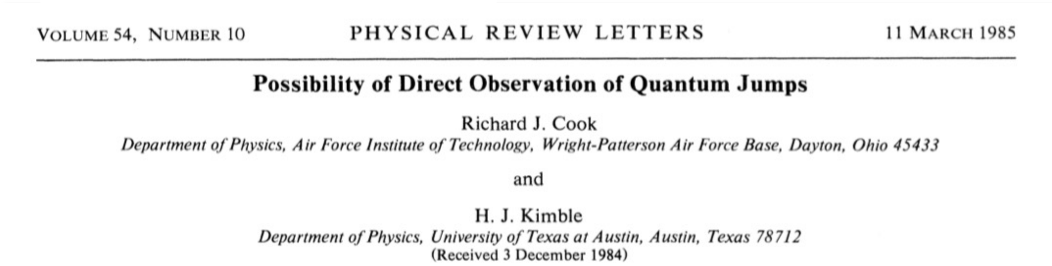
Quantum jumps (1980s)

Single ions

PRA 22, 1137 (1980)

Phys. Lett. 82A, 75 (1981)





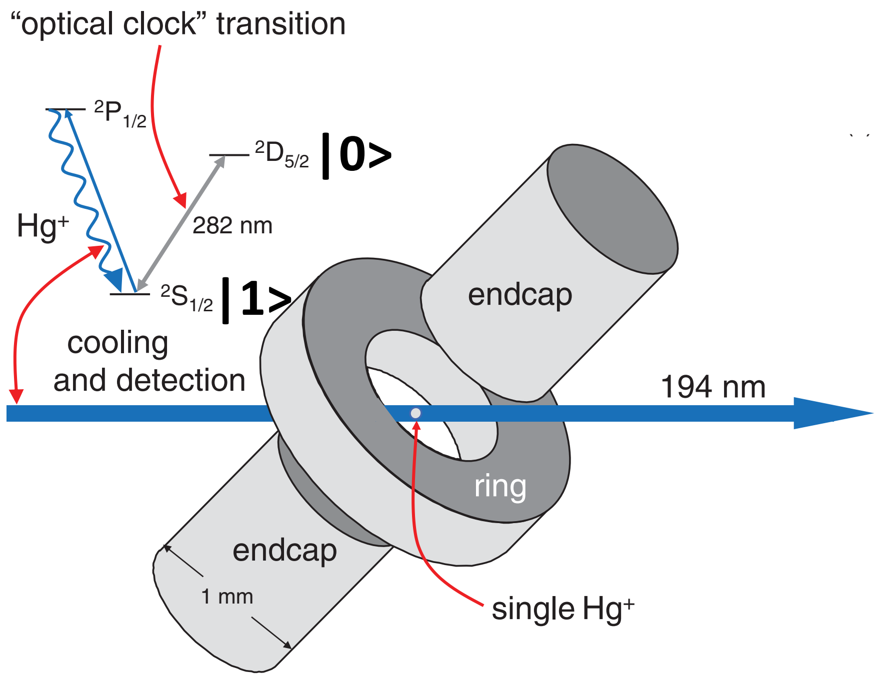
VOLUME 54, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 1985

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

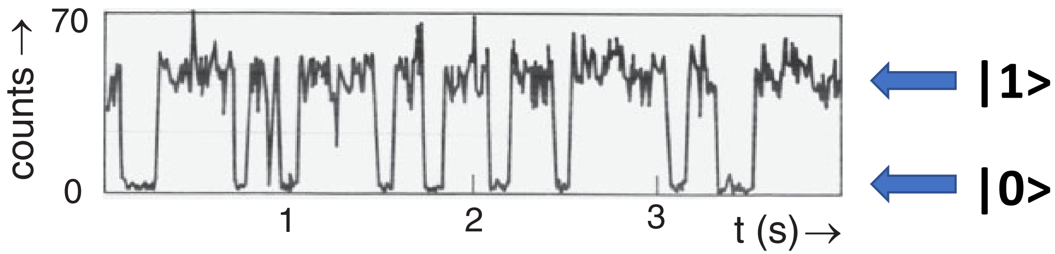
and

H. J. Kimble
Department of Physics, University of Texas at Austin, Austin, Texas 78712
(Received 3 December 1984)



Quantum jumps

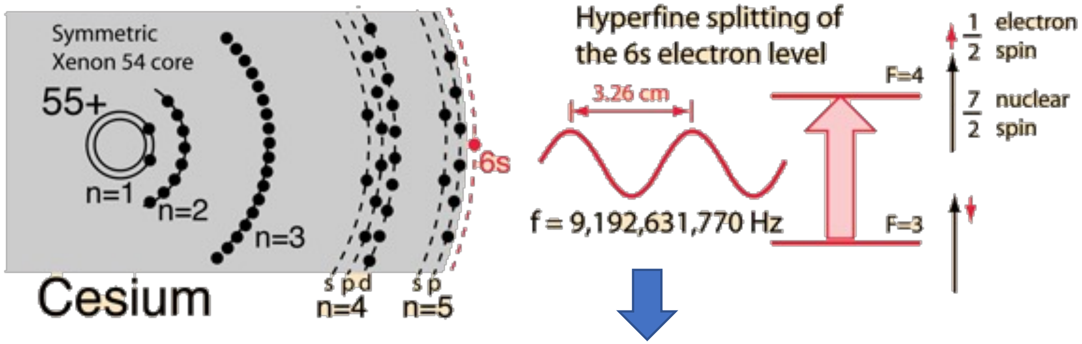
Dehmelt	PRL 56, 2797 (1986)
Blatt, Toscheck	PRL 57, 1696 (1986)
Wineland	PRL 57, 1699 (1986)



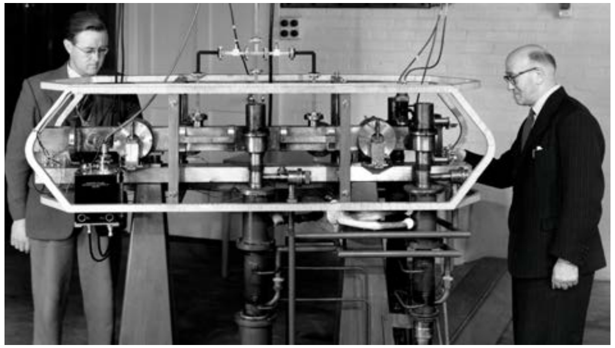
D. Wineland *Rev. Mod. Phys.* **85**, 1103 (2013).

Time standards / clocks

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



1955 Images: NPL



Reduce motion

2018 NPL UK (Cs atoms)

5.4×10^{-13} at 1 s

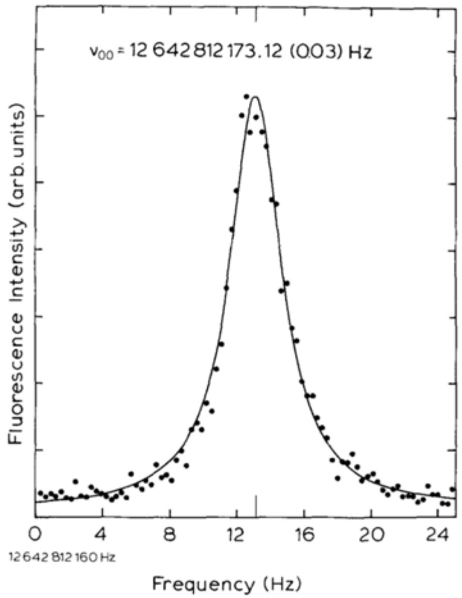
4.0×10^{-16} at 20d

$^{171}Yb^{+}$

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 → THz

$^{171}Yb^{+}$ F-state

(3 year lifetime)

Accuracy: **3.0×10^{-18}**

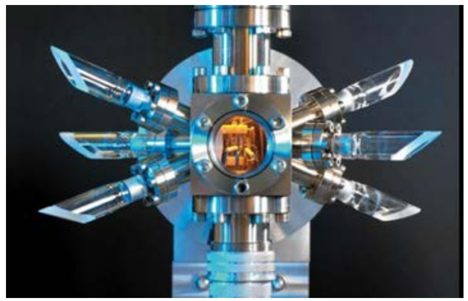
PTB Germany

PRL **116**, 063001 (2016)

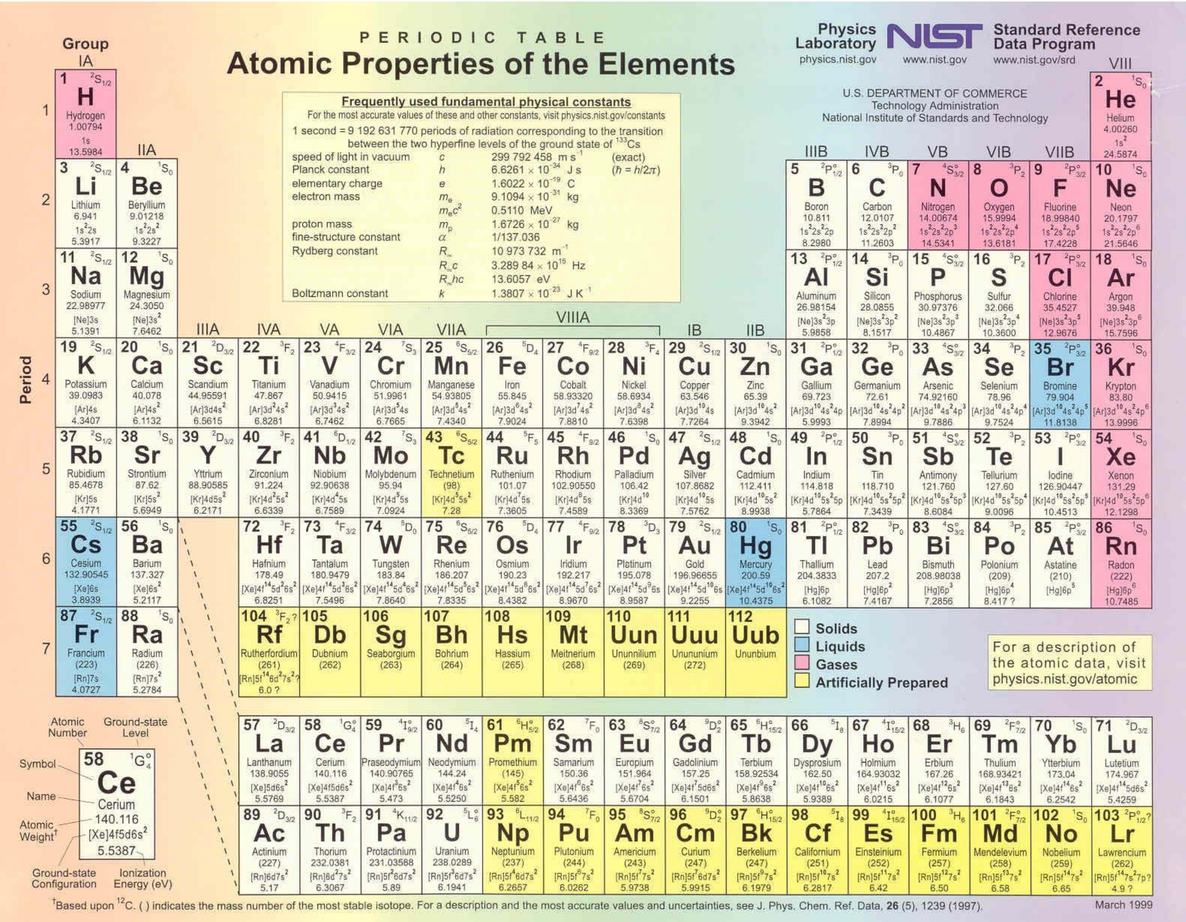
Accuracy: **9.4×10^{-19}**

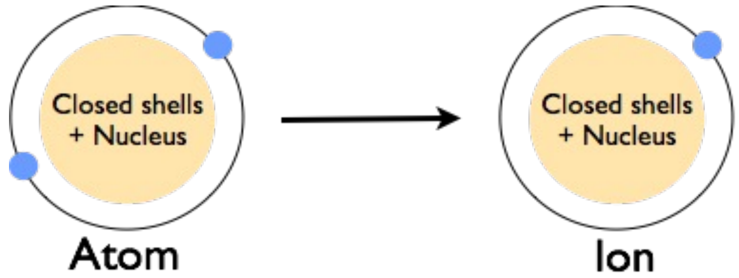
NIST USA

PRL **123**, 033201 (2019).

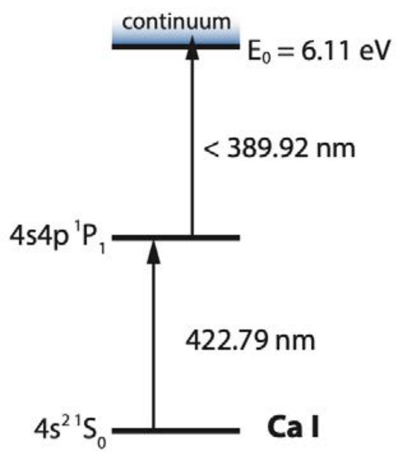


Which elements are good for storing quantum bits?

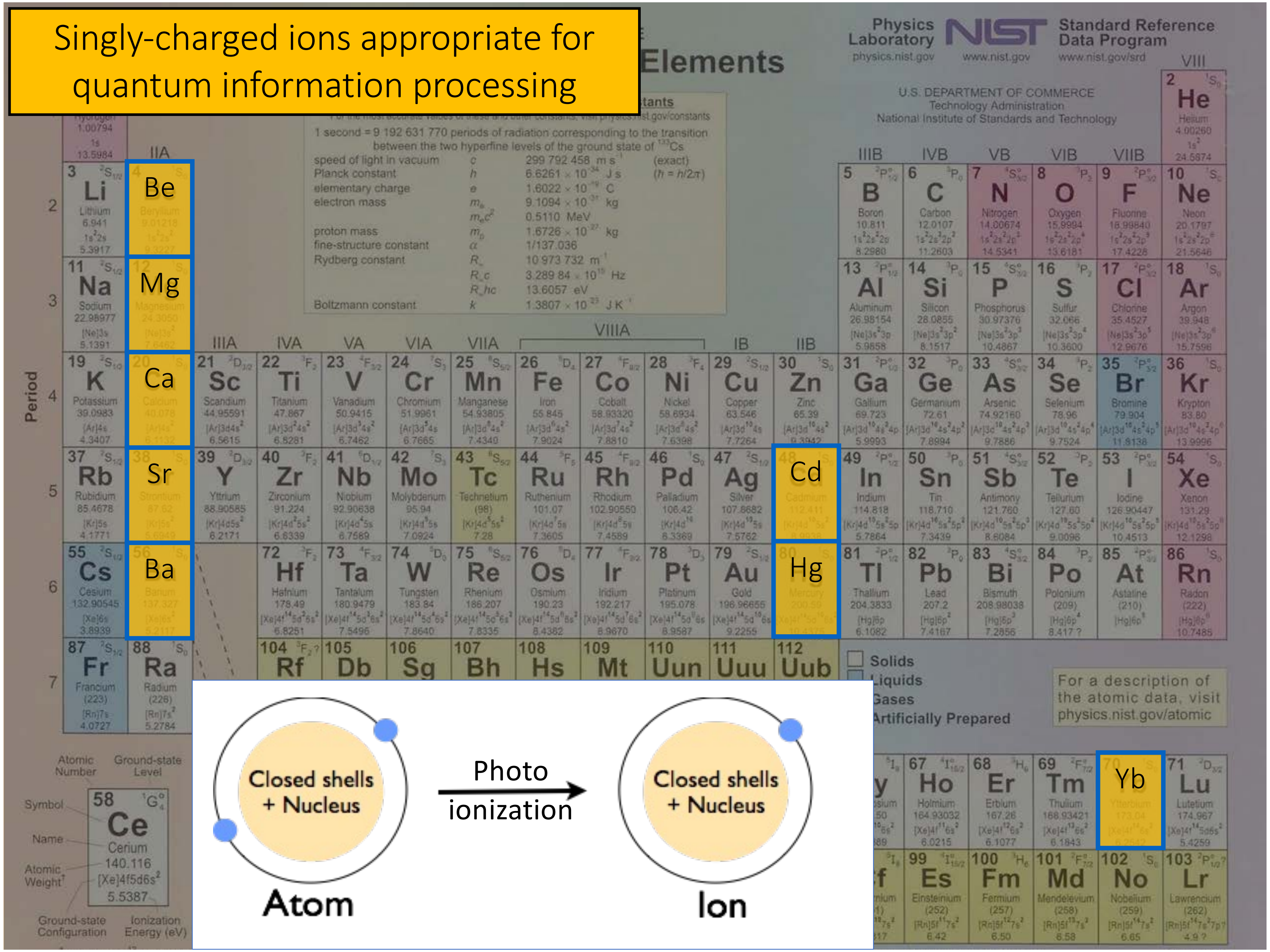




Photoionization

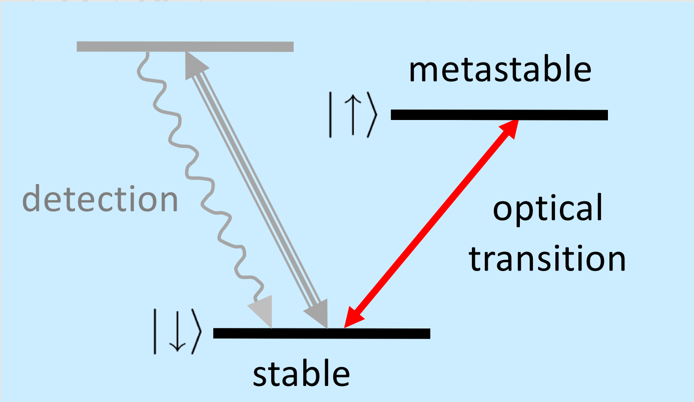


Singly-charged ions appropriate for quantum information processing



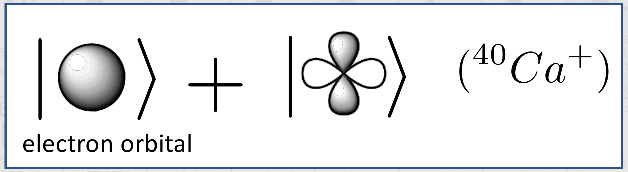
Types of trapped ion quantum bits

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



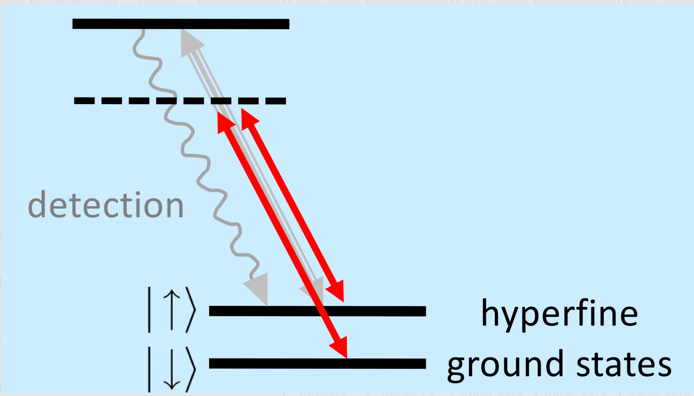
"optical qubit"

qubit manipulation requires ultrastable laser



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

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



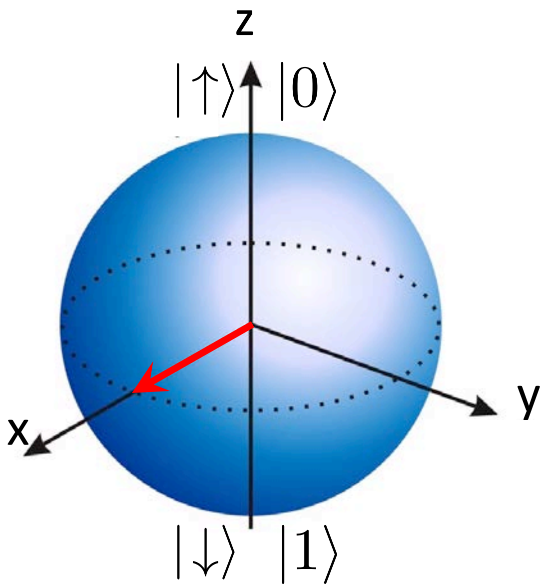
"hyperfine qubit"

qubit manipulation with microwaves or lasers (Raman transitions)

$$|\downarrow\uparrow\rangle + |\uparrow\uparrow\rangle \quad (^{43}Ca^+)$$

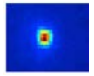
electron spin nuclear spin

Encoding and reading out a qubit in an ion



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

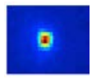
$p_{|\uparrow\rangle} = |\alpha|^2$ 

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

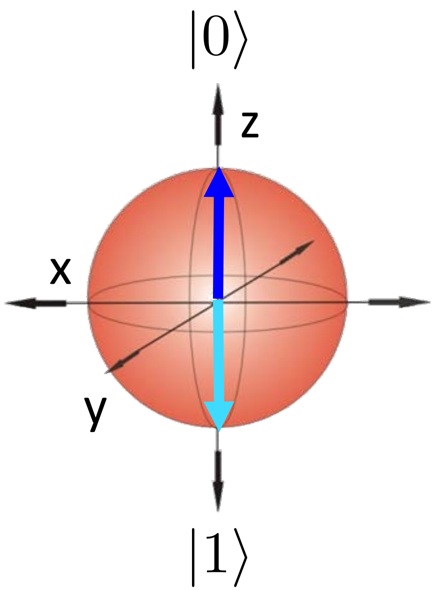
“Electron shelving”
Dehmelt, H. G. (1982).

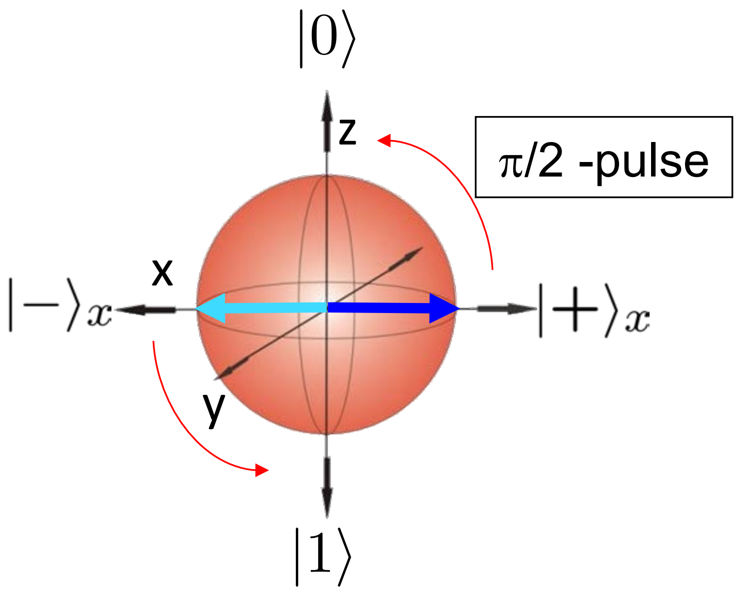
$\tau \approx 7\,\mathrm{ns}$ **$P_{1/2}$**

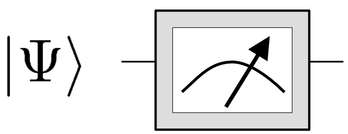
$\tau \approx 1.1\,\mathrm{s}$ **$D_{5/2}$** 

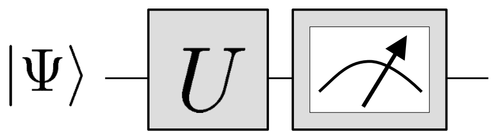
$S_{1/2}$ 

Measurement of expectation values / error bar

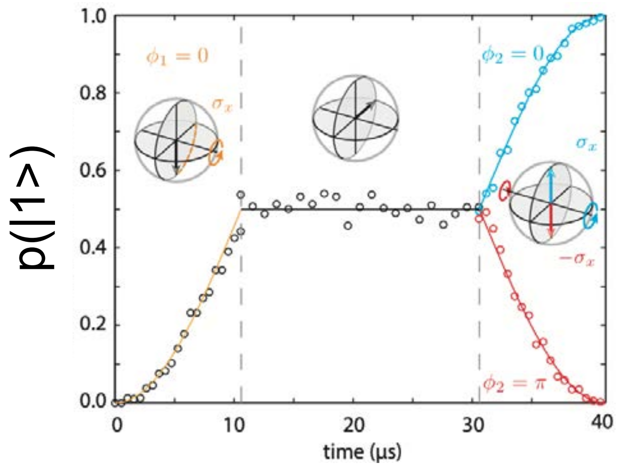








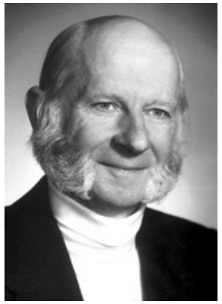
Quantum Projection Noise

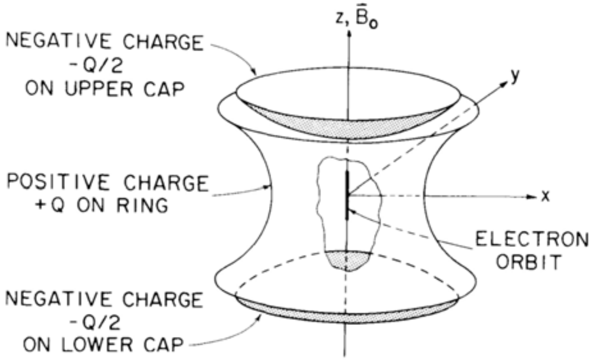


QPN: Itano, W. M. *et al.*, *Physical Review A* **47**, 3554–3570 (1993).

Trapping ions – two different types of ion traps

Penning trap

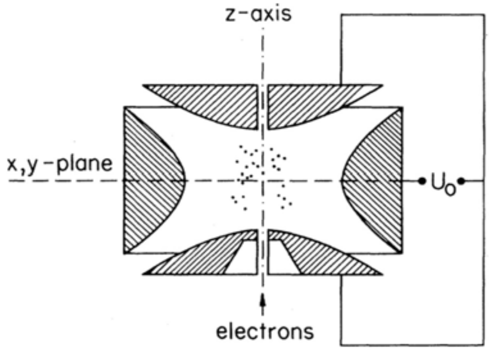

Hans Dehmelt



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).

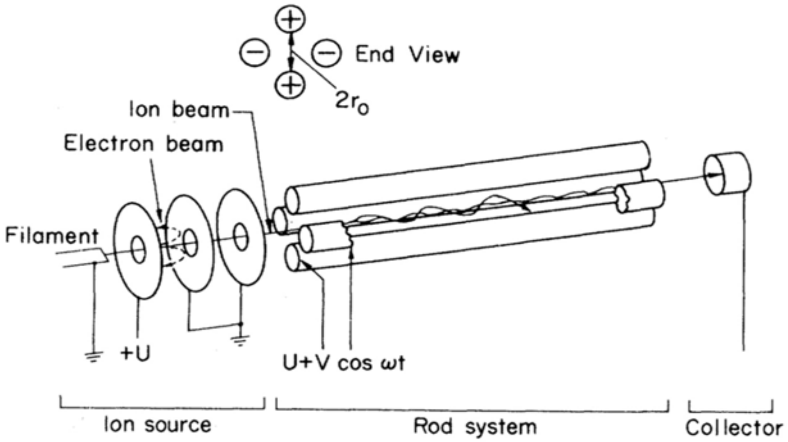
W. Paul, Rev. Mod. Phys. **62,** 531–540 (1990).

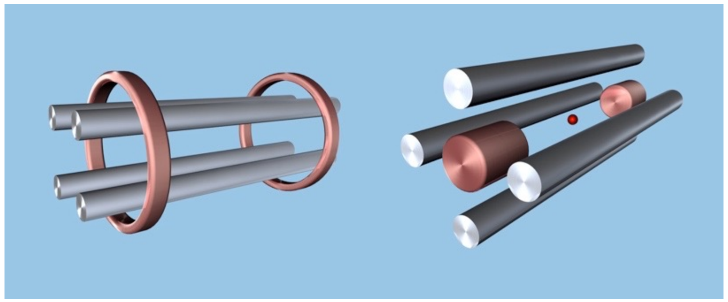
Paul traps over the years

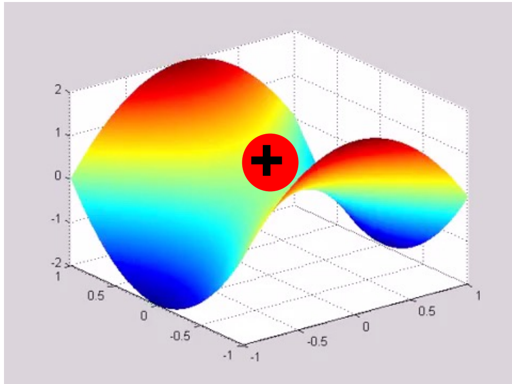
Ein neues Massenspektrometer ohne Magnetfeld

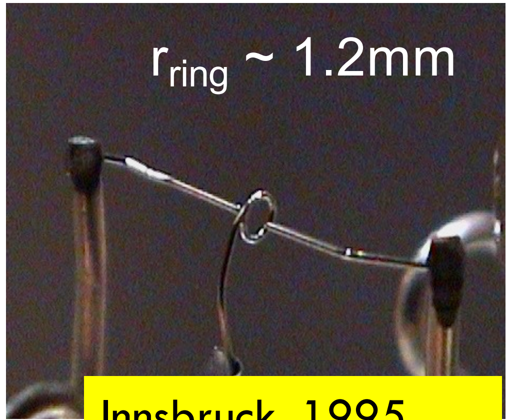
Von Wolfgang Paul und Helmut Steinwedel
Physikalisches Institut der Universität Bonn

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

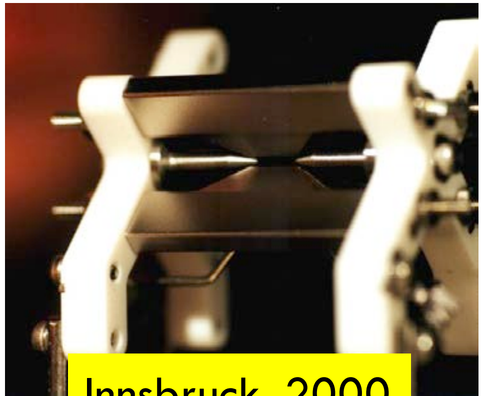




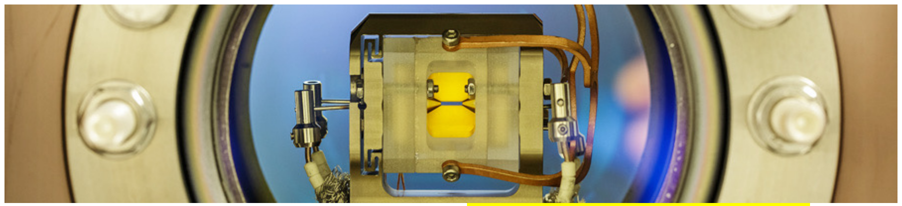




Innsbruck, 1995

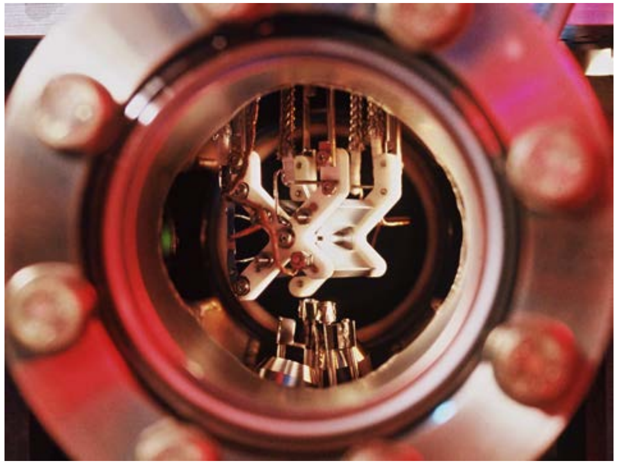


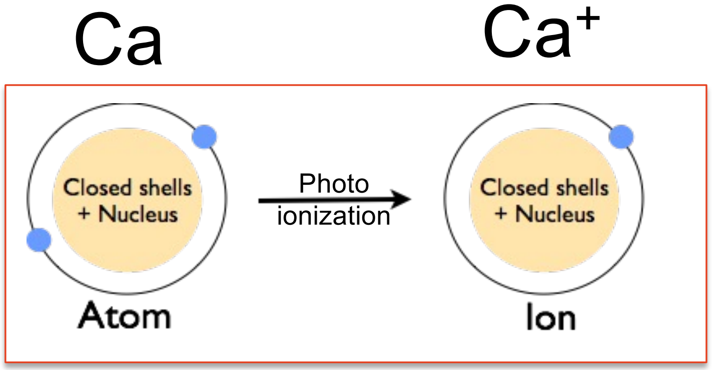
Innsbruck, 2000

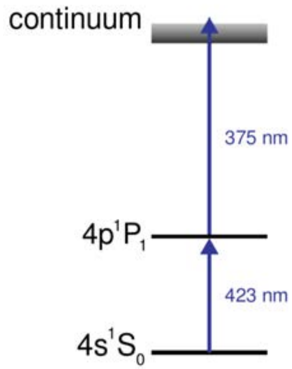


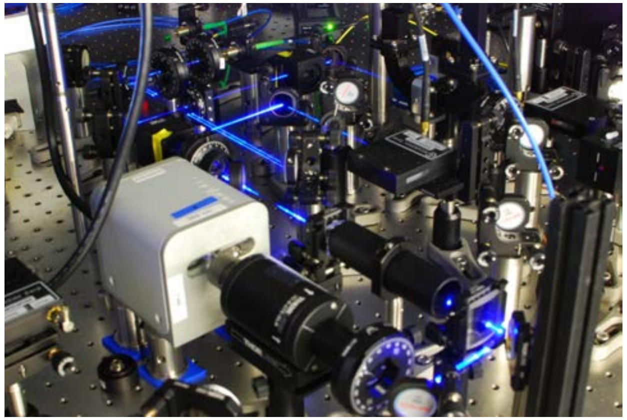
Innsbruck, 2012

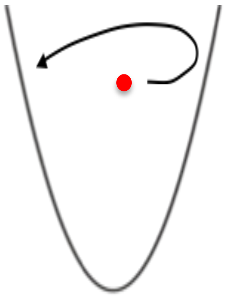
Ion loading and laser cooling

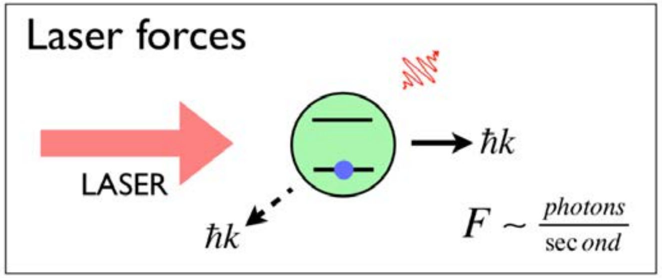






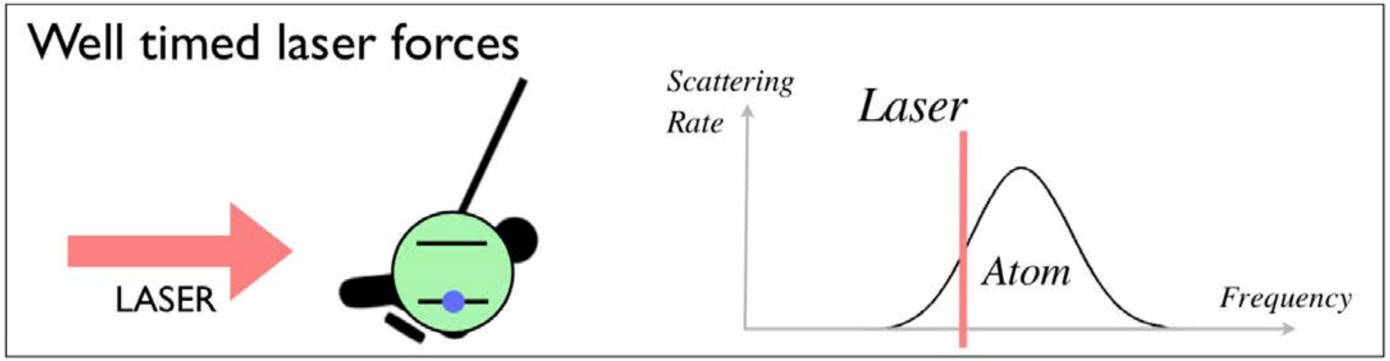


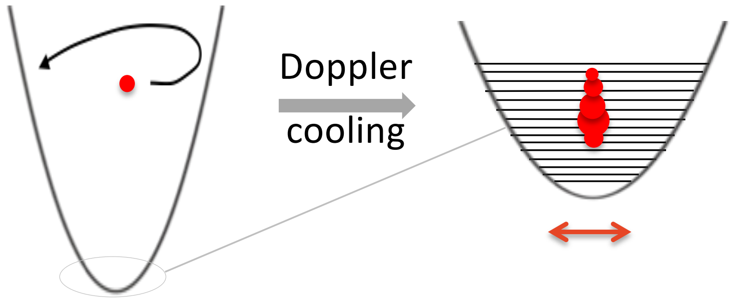




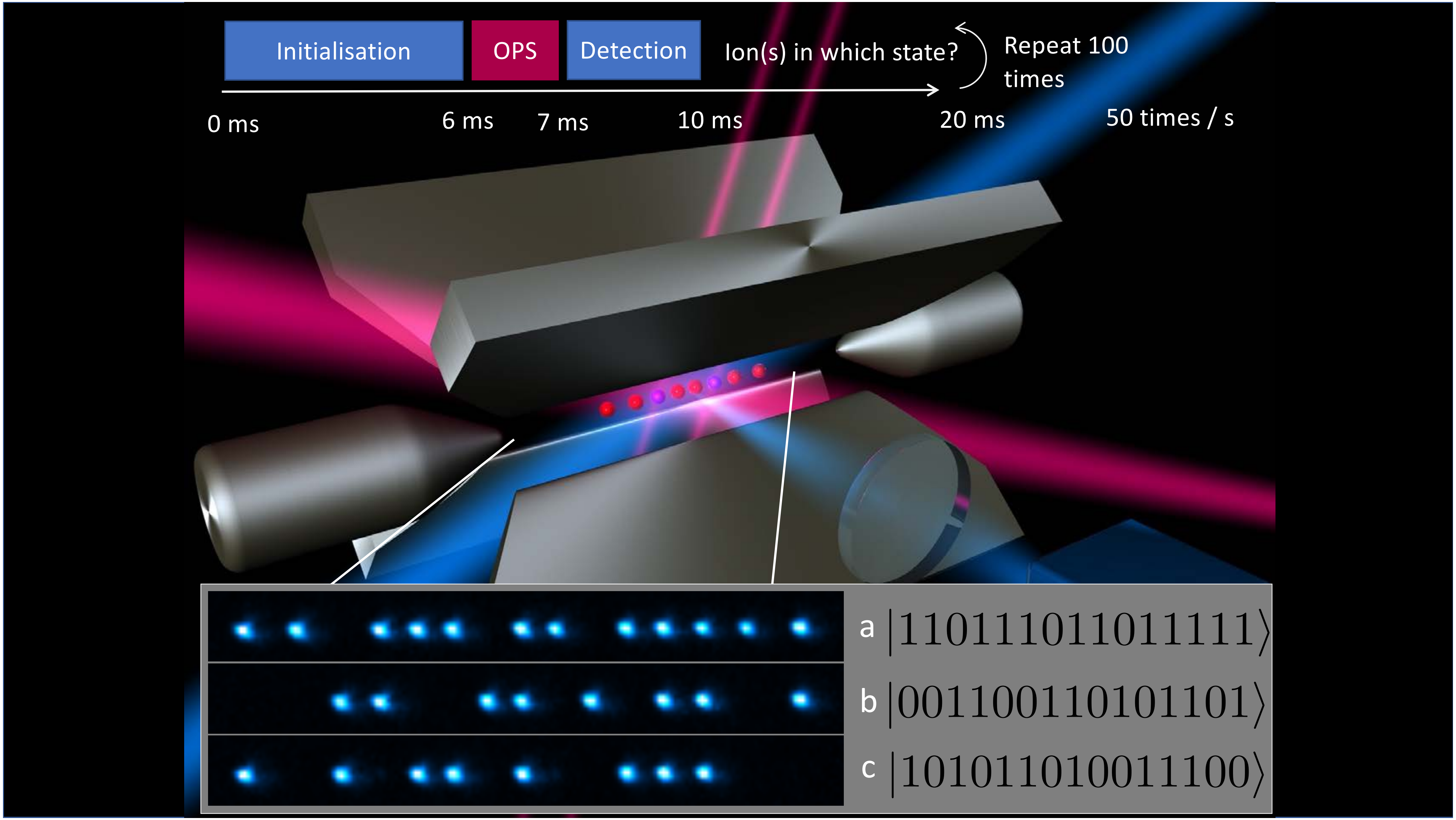
D. J. Wineland and W. M. Itano, Phys Today **40**, 34 (1987).

Doppler cooling

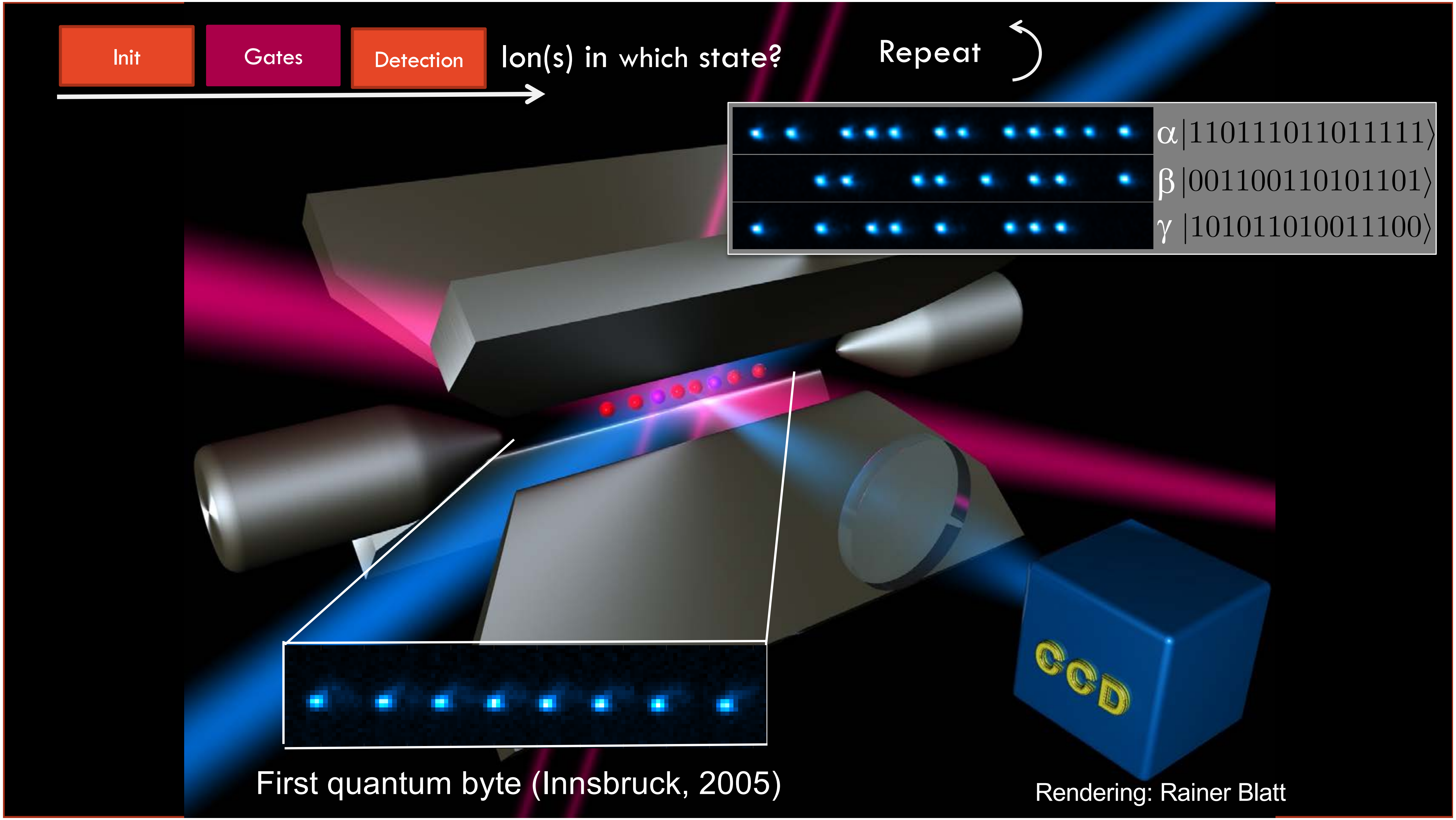




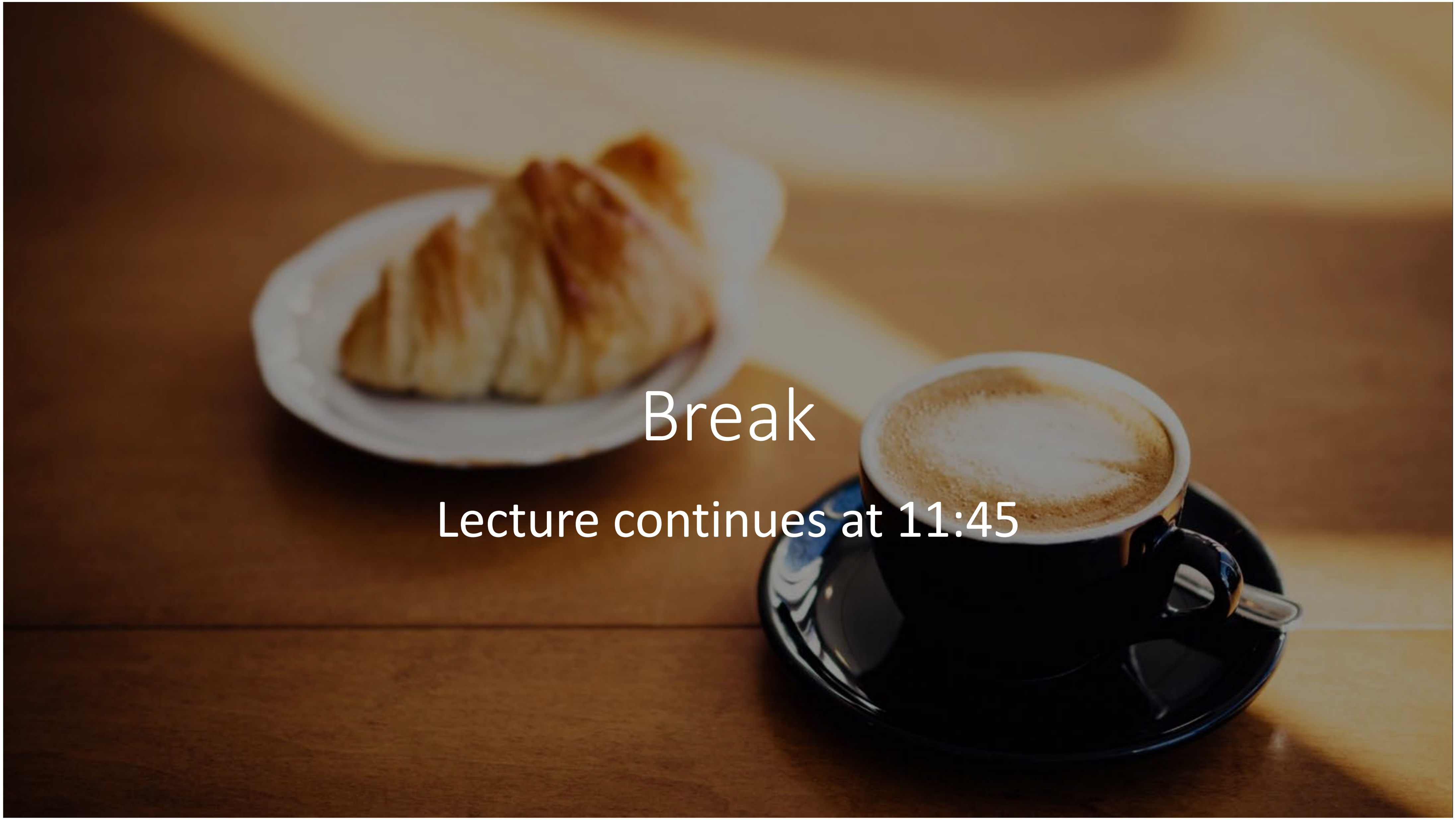
Wineland, D. J. & Itano, W. M. - Laser cooling of atoms. *Physical Review A* **20**, 1521–1540 (1979).



Initialisation
OPS
Detection
Ion(s) in which state?
Repeat 100 times
0 ms
6 ms
7 ms
10 ms
20 ms
50 times / s
a |110111011011111⟩
b |001100110101101⟩
c |101011010011100⟩



Init
Gates
Detection
Ion(s) in which state?
Repeat
α |110111011011111⟩
β |001100110101101⟩
γ |101011010011100⟩
CCD
First quantum byte (Innsbruck, 2005)
Rendering: Rainer Blatt


Break
Lecture continues at 11:45