



Think BigSmall

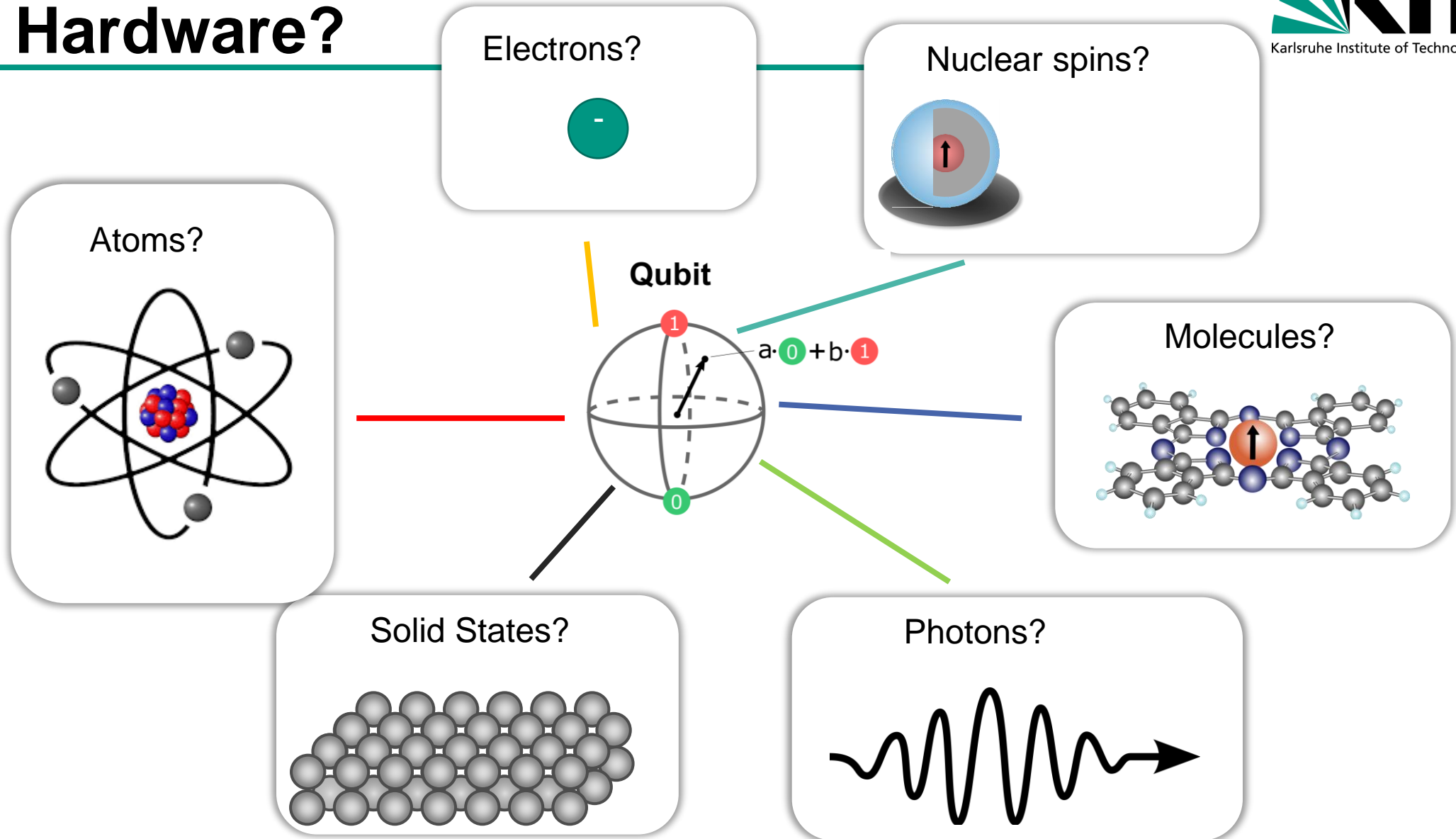
Quantenkontrolle einzelner Atome mit Rastertunnelmikroskopie

TTProf. Dr. Philip Willke | KIT Physikalisches Institut



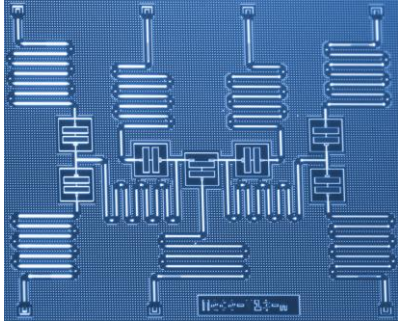
Twitter: @WillkePhilip
Homepage: www.atomholics.de

Qubit Hardware?



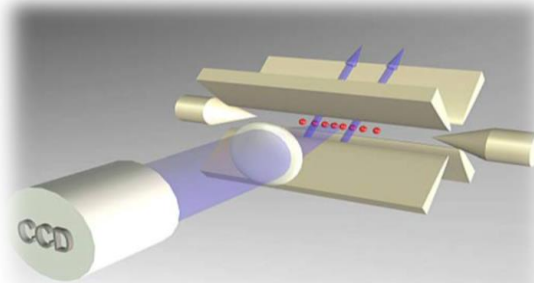
Different Architectures

■ Superconducting Quantum Circuits



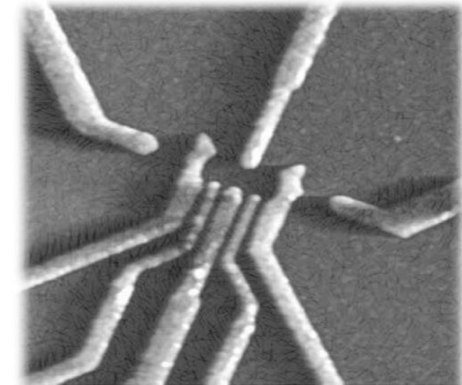
IBM, Google

■ Trapped Ions



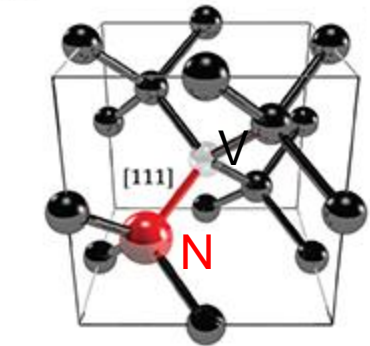
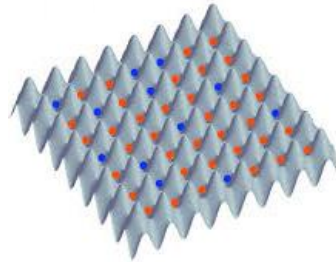
Quantinuum, IonQ

■ Semiconductor Quantum Dots: Silicon Spins



Intel

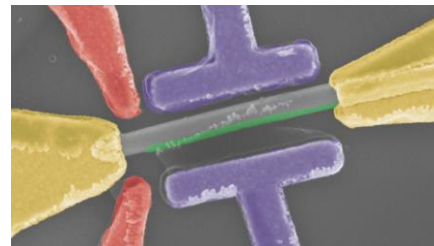
■ Neutral Atoms/ Rydberg Atoms



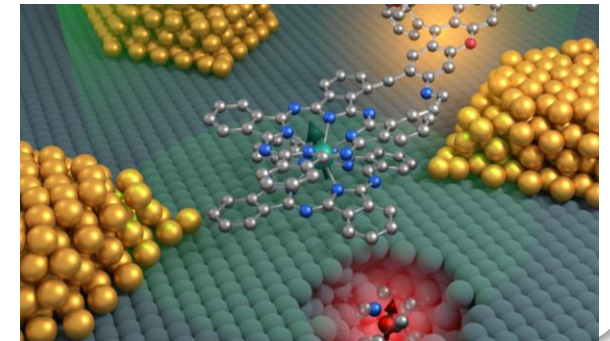
■ Color Centres in Diamond

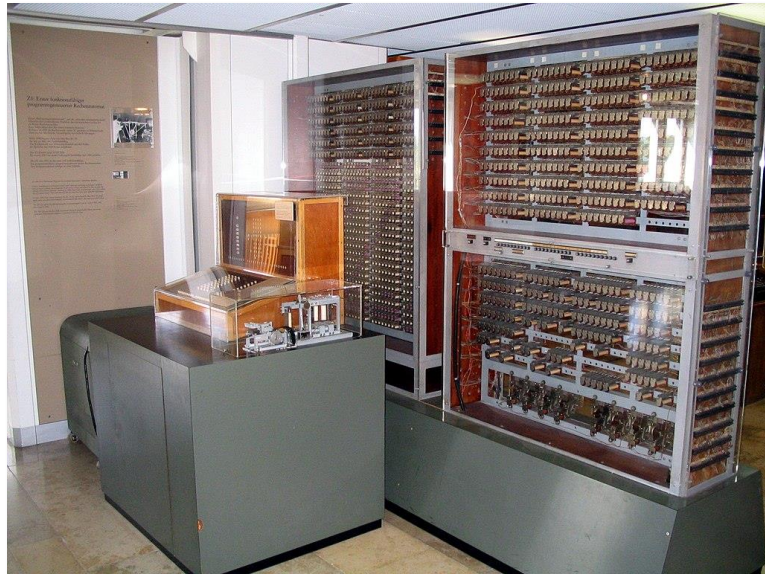
■ Topological Qubits

Microsoft

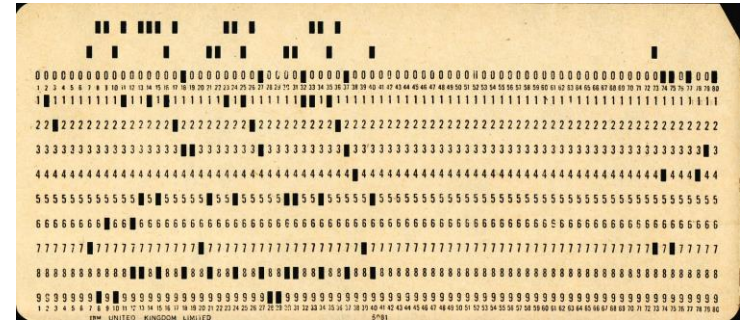


■ Molecules



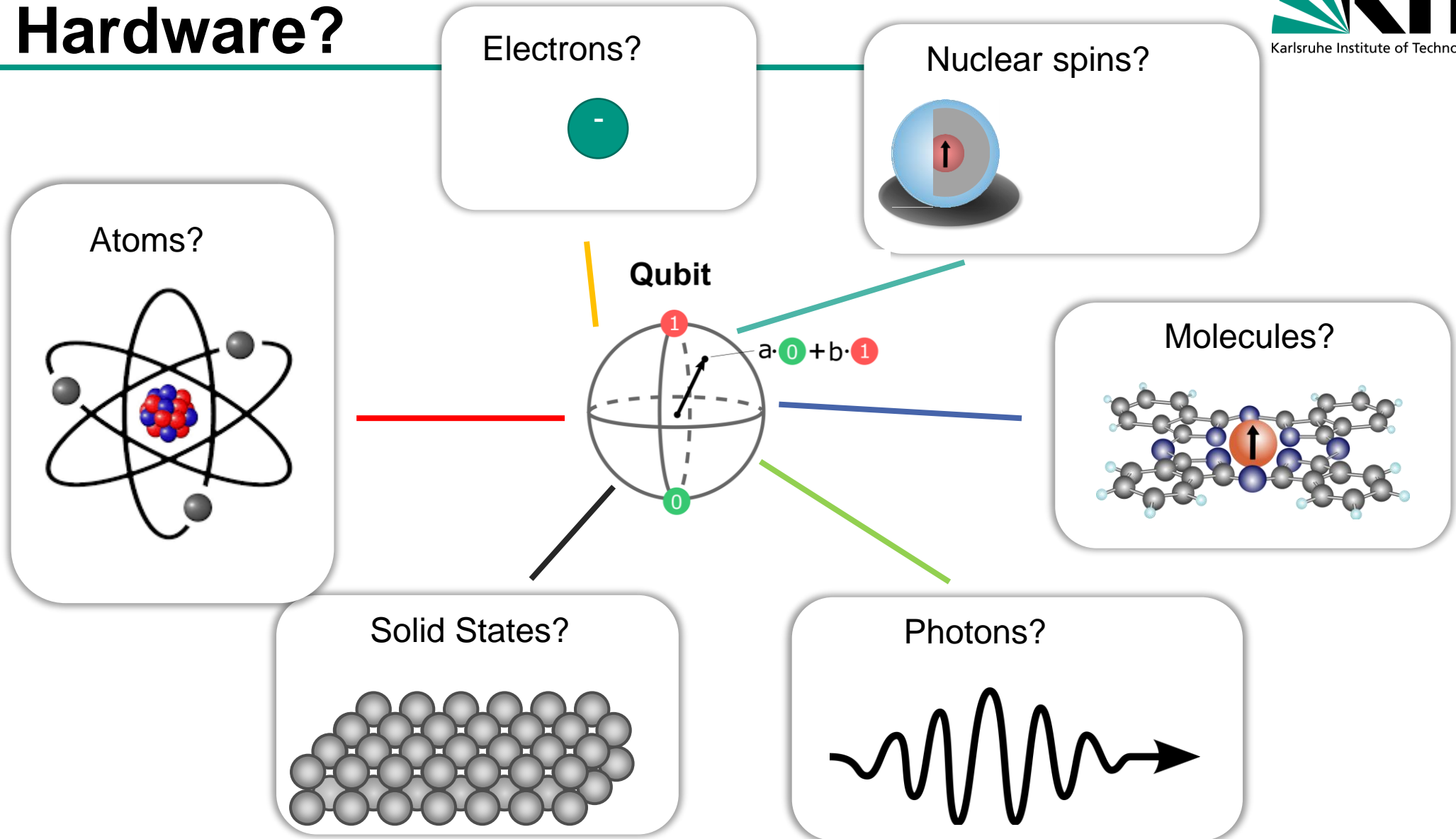


**Zuse Z3
Electro-magnetic Relais**



IBM punched card

Qubit Hardware?

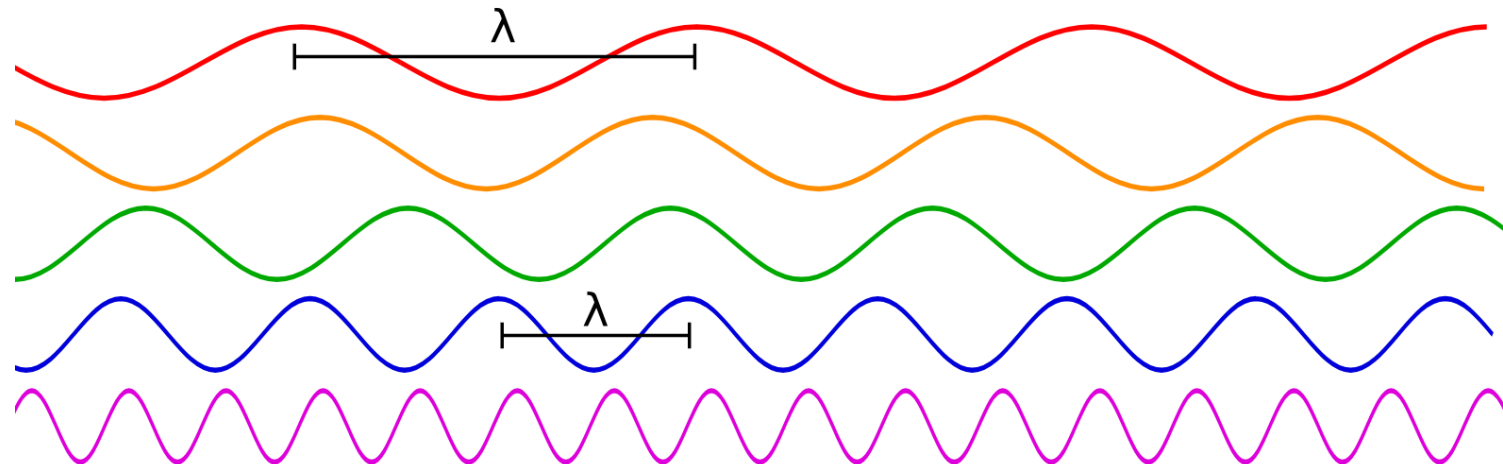


Atome sehen

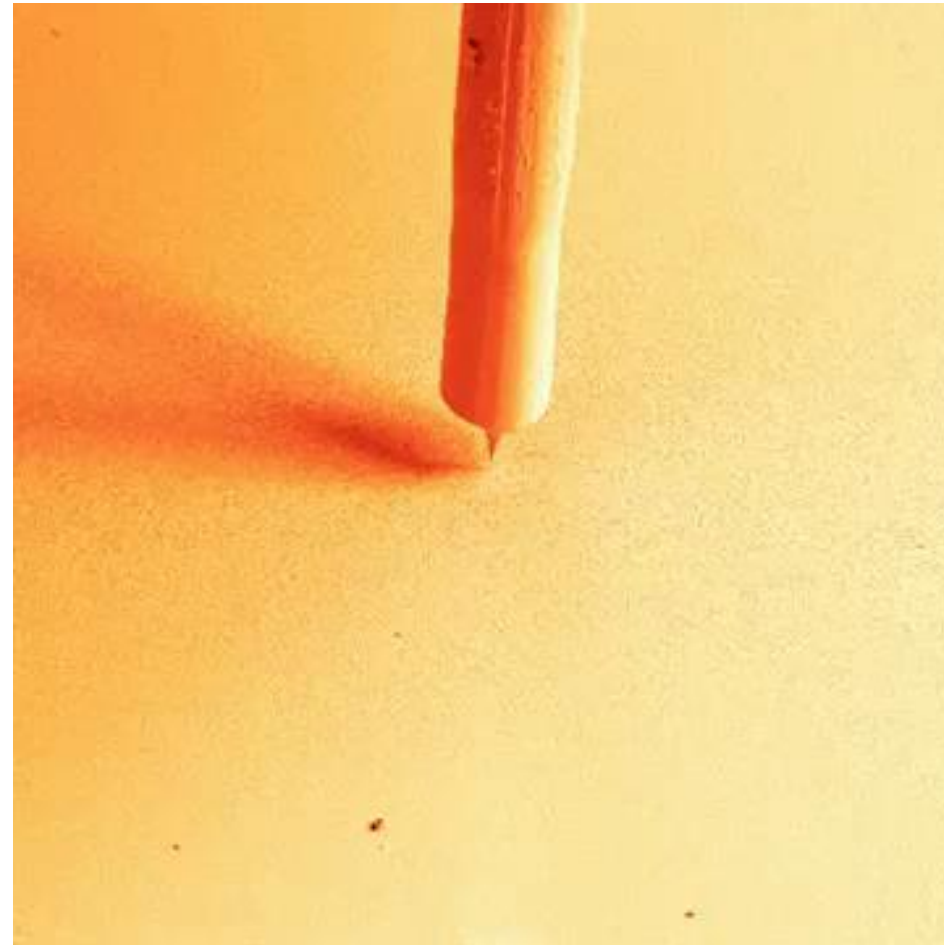
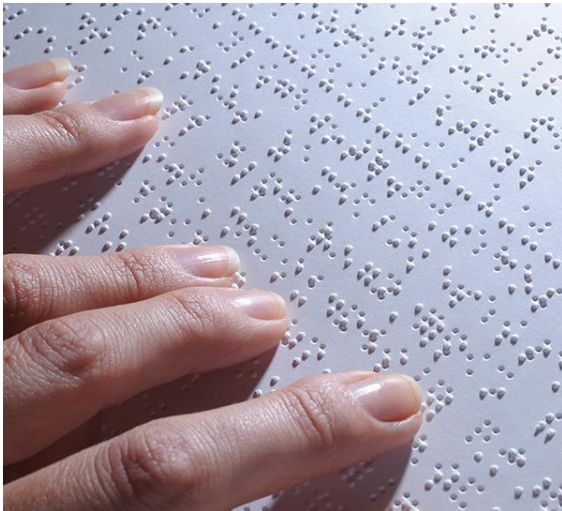


Licht ist zu groß für Atome!

Licht ist eine elektromagnetische Welle

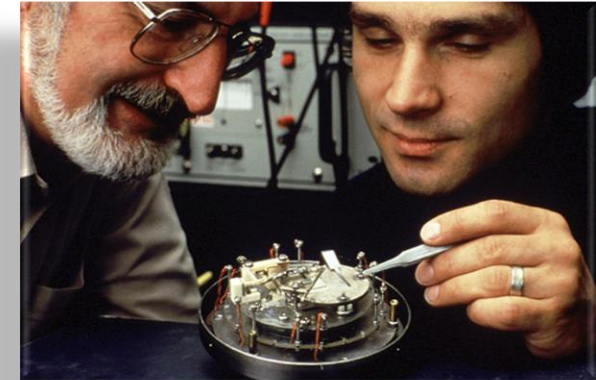
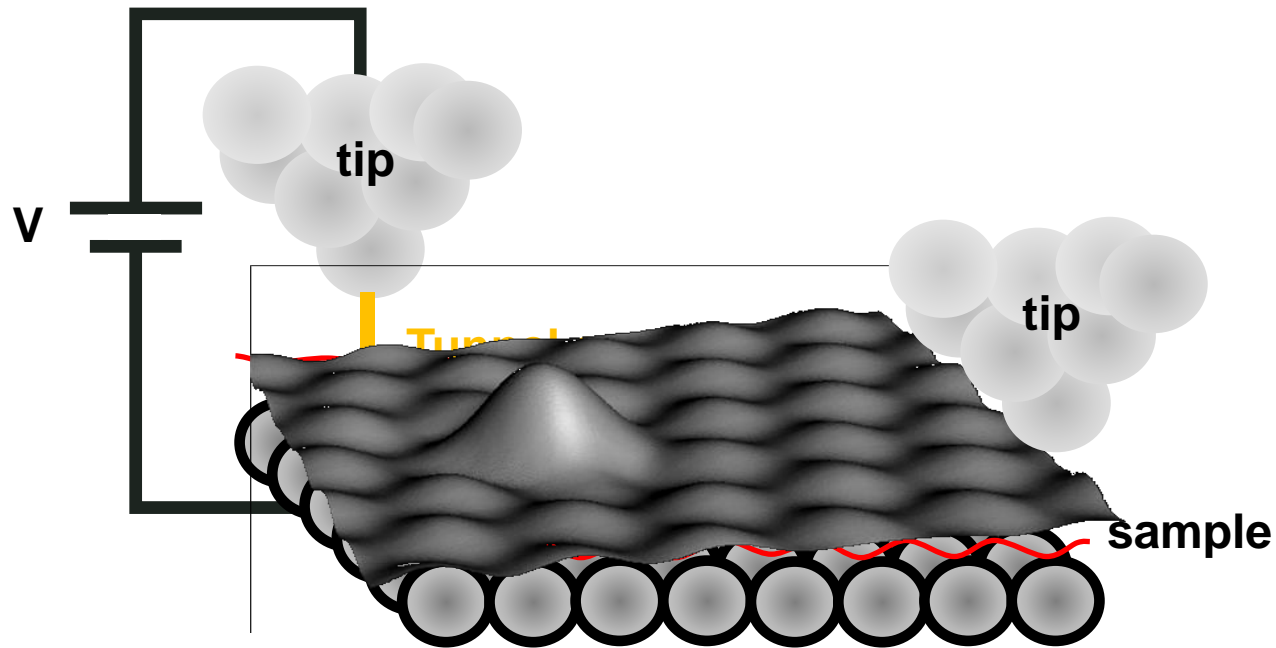


Atome “fühlen”



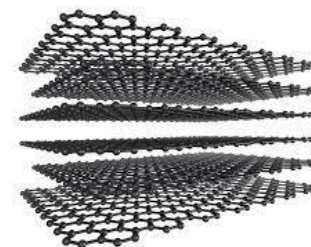
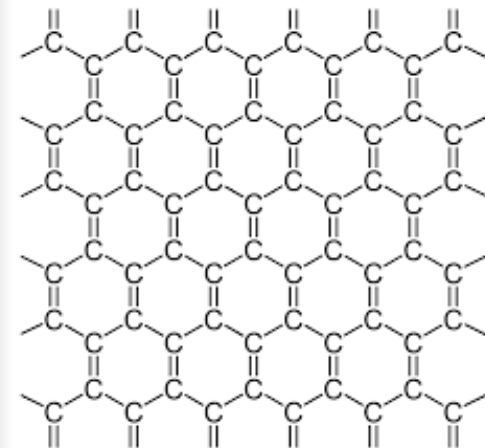
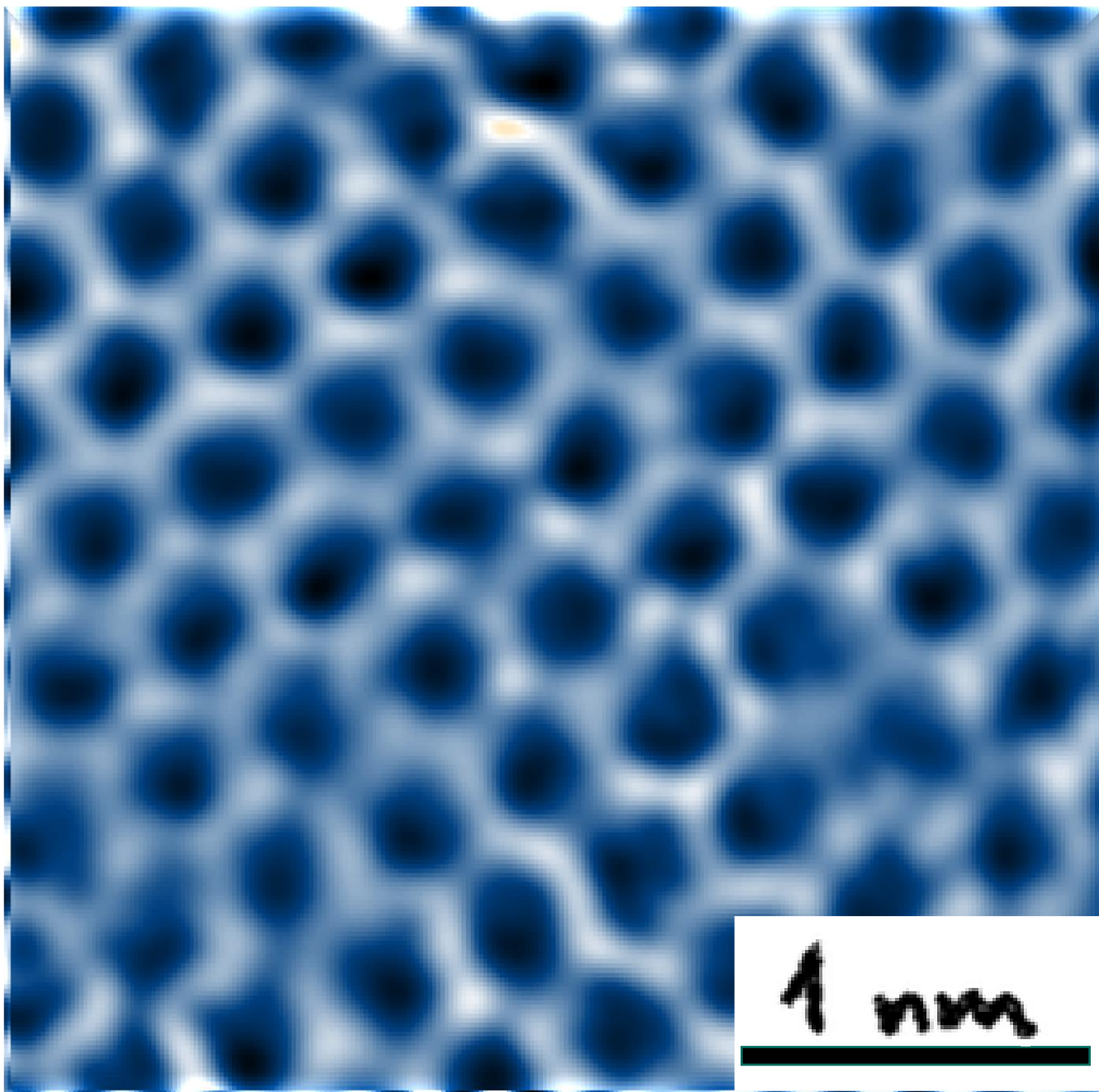
Video: FZJ

Die Erfinder des Rastertunnelmikroskops

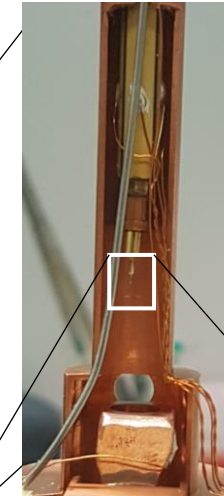
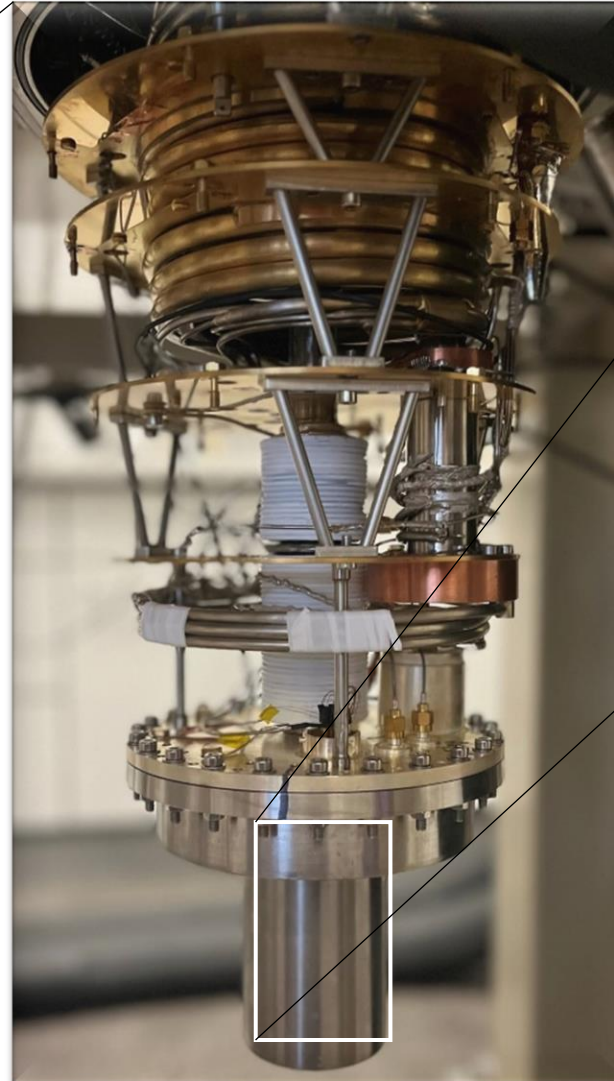


**Georg Binnig & Heinrich Rohrer
(Nobelpreis für Physik 1986)**

Graphit

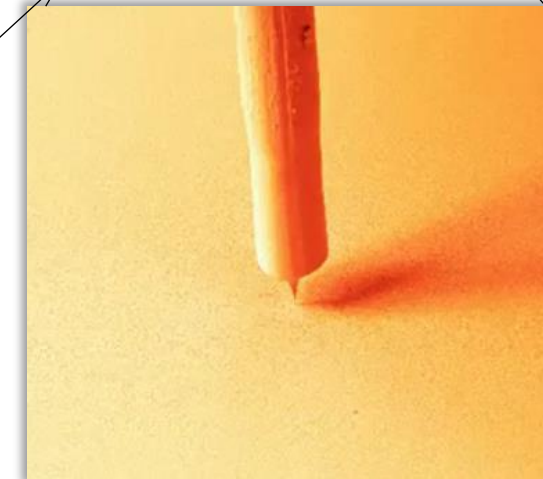


Scanning Tunneling Microscope



Experimental Conditions

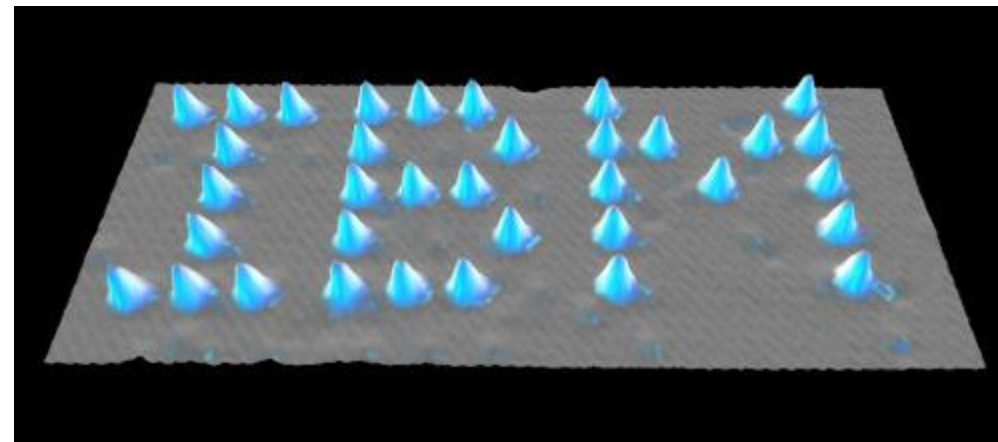
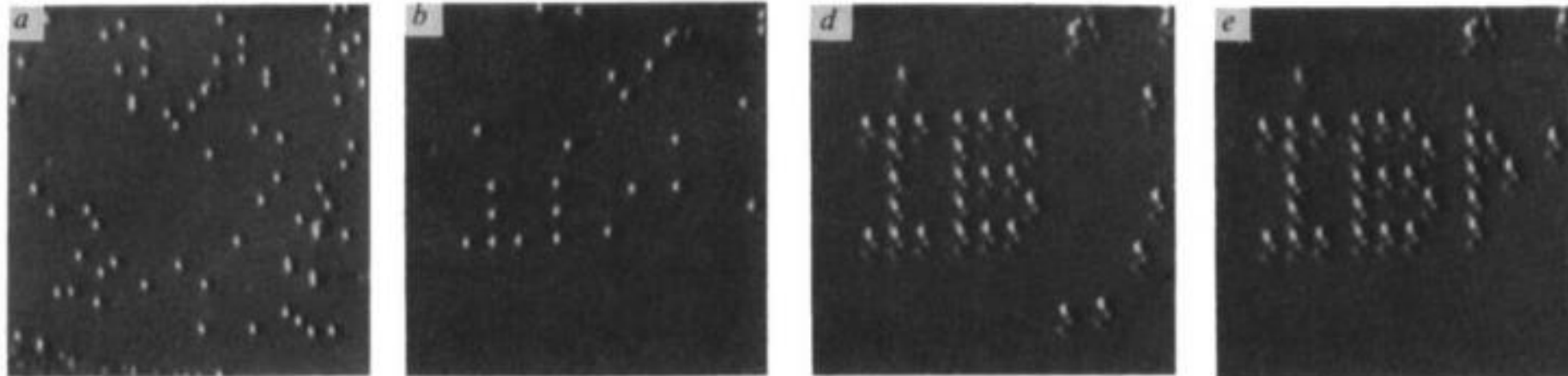
- Temperatures $T < 1\text{K}$
- Experiments in ultra high vacuum
- For ESR magnetic fields up to 1 Tesla



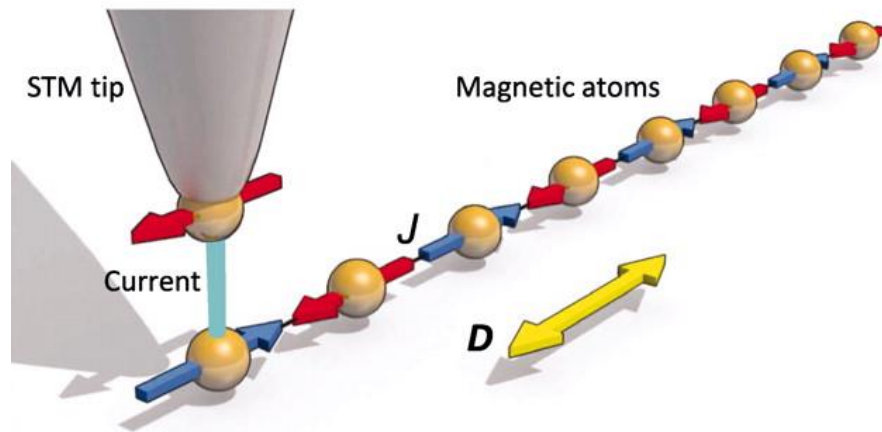
Atom Manipulation



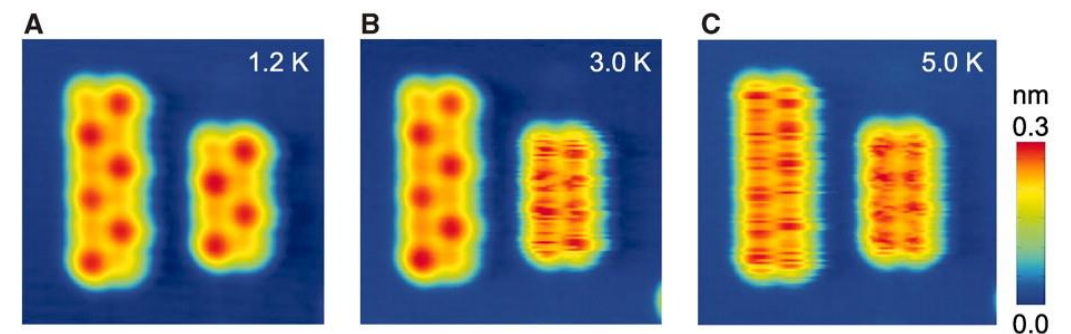
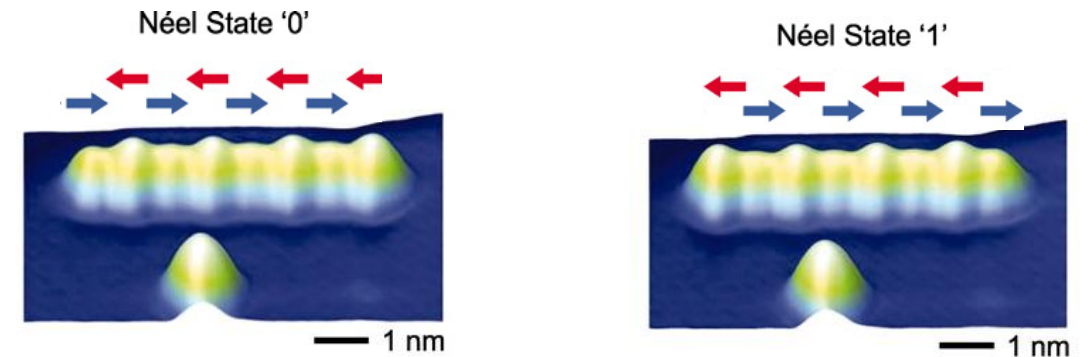
Xenon Atoms on a Ni surface



Bistable AFM array of Fe atoms

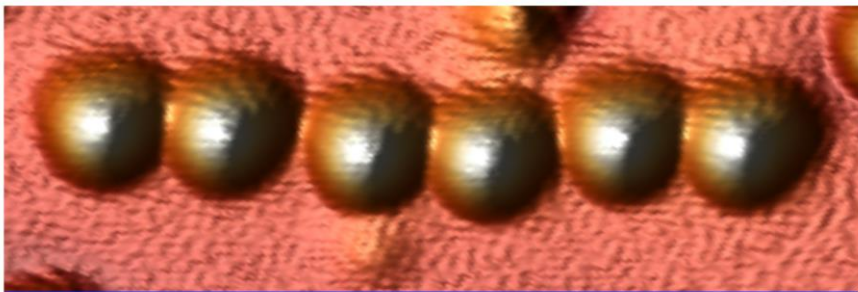


A spin-polarized STM tip reads and writes the magnetic state of the AFM array by magnetoresistive tunneling.



Selbstgebaute atomare Speicher

Register aus 6 Atomen:



Strom

1	0	1	0	1	0
---	---	---	---	---	---

32 (2⁵) + 8 (2³) + 2 (2¹) = 42

Stack 1: S (green), N (red) = 1
Stack 2: N (red), S (green) = 0



WIKIPEDIA
Die freie Enzyklopädie

42 (Antwort)

Die Antwort **42** ist ein Zitat aus der mehrfach verfilmten Roman- und Hörspielreihe *Per Anhalter durch die Galaxis* des englischen Autors Douglas Adams.

Im Roman ist „42“ die von einem Supercomputer nach einigen Millionen Jahren Rechenzeit gegebene Antwort auf die Frage „nach dem Leben, dem Universum und dem ganzen Rest“ (englisch *“life, the universe and everything”*), mit der die Protagonisten letztlich nichts anfangen können, weil die Frage zu vage gestellt war.



Per Anhalter durch die Galaxis...

F. Natterer, ... PW, et al., *Nature* **543**, 226-228 (2017)

A. Singha*, P. Willke*, T. Bilgeri* et al., *Nature Commun.* (2021)

Quantum Science of Atoms on Surfaces

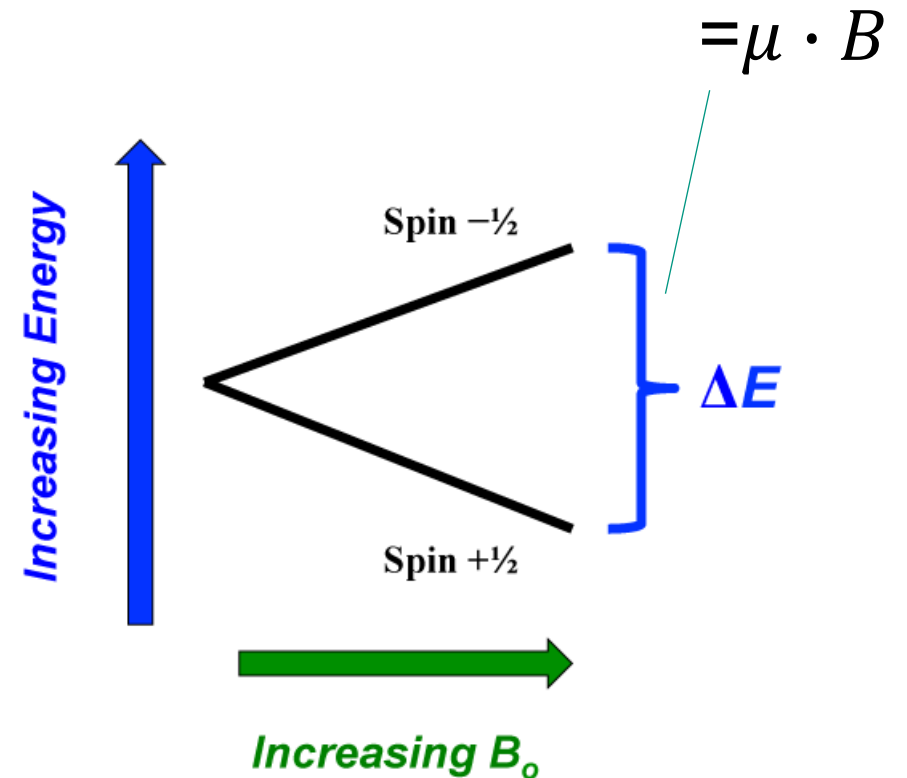
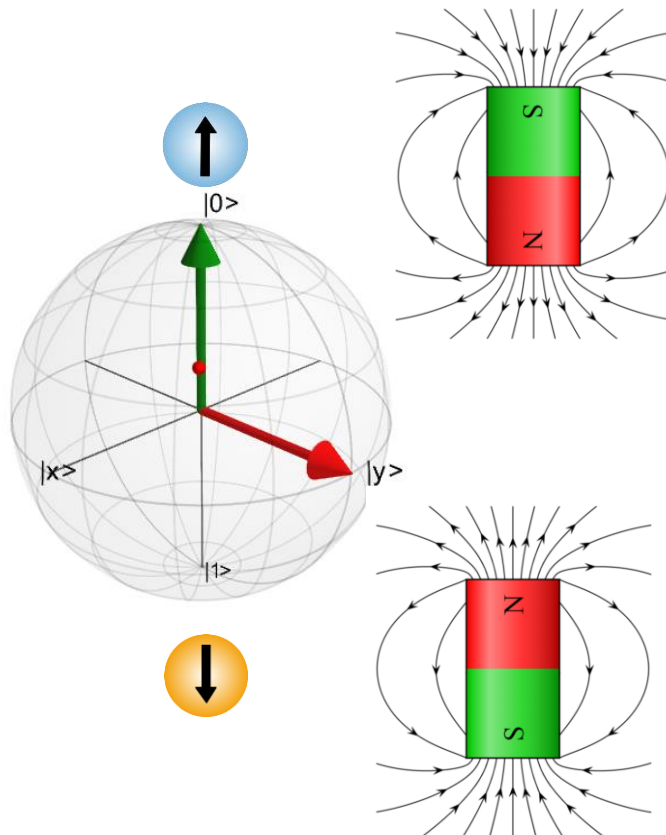


Spin-Qubits

- Spin is one of two types of atomic angular momentum (rotation)
- Associated with a magnetic moment

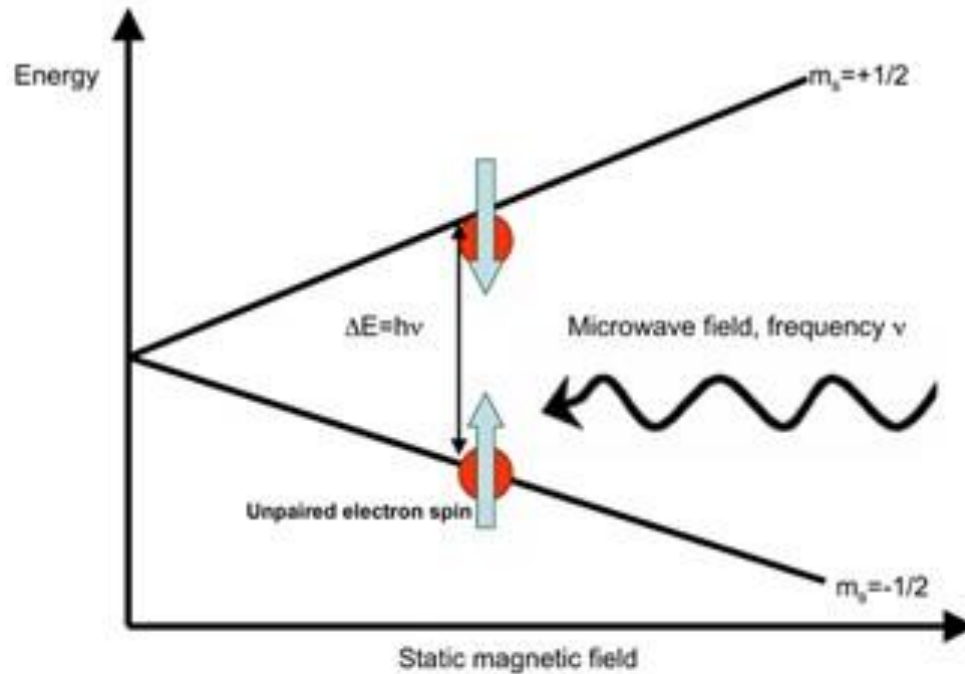
- Zeeman Interaction: Energy difference increases linearly with B

magnetic field



Spin-Qubits

- How do we coherently rotate a spin now?
→ Spin resonance



$$h\nu = g_e \mu_B B_0$$

Planck-constant Microwave-frequency g-factor (magnitude of magnet) Bohr-magneton (unit of atomic magnets) Magnetic field

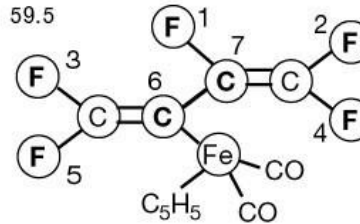
- Light/Microwaves are a time-dependent magnetic field, that can rotate the spin between its two states
- Same process as realized in an MRI



Spin-Qubits

- Nuclear spins

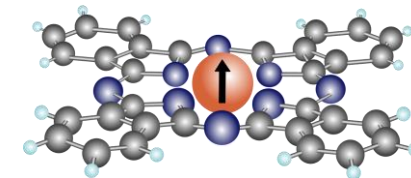
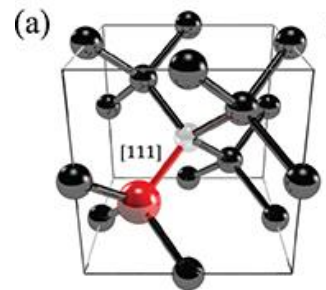
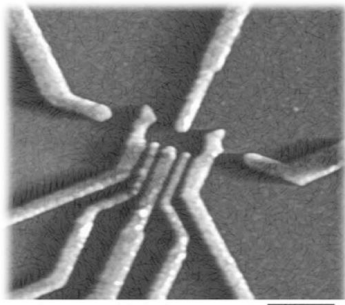
i	$\omega_i/2\pi$	$T_{1,i}$	$T_{2,i}$	J_{7i}	J_{6i}	J_{5i}	J_{4i}	J_{3i}	J_{2i}
1	-22052.0	5.0	1.3	-221.0	37.7	6.6	-114.3	14.5	25.16
2	489.5	13.7	1.8	18.6	-3.9	2.5	79.9	3.9	
3	25088.3	3.0	2.5	1.0	-13.5	41.6	12.9		
4	-4918.7	10.0	1.7	54.1	-5.7	2.1			
5	15186.6	2.8	1.8	19.4	59.5				
6	-4519.1	45.4	2.0	68.9					
7	4244.3	31.6	2.0						



<https://www.nature.com/articles/414883a>

- Defects and electrons in semiconductors and insulators

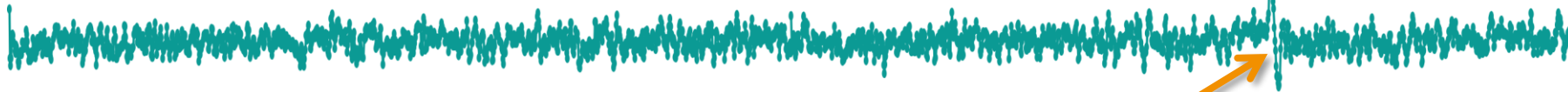
- Molecular and Atomic Spins



Single Atom Electron Spin Resonance

$$hf_0 = g\mu_B B \Delta m_S$$

$B_z = 213$ mT



$B_z = 196$ mT



$B_z = 183$ mT



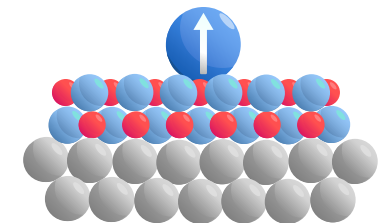
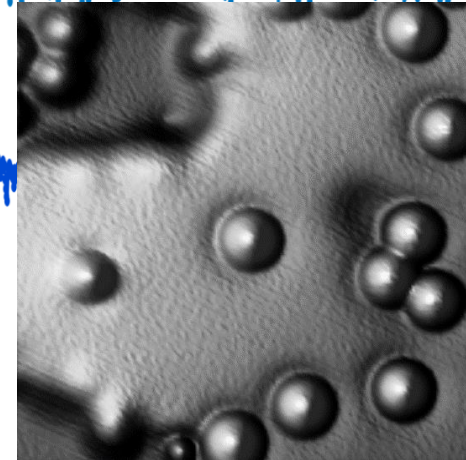
$B_z = 170$ mT



50 fA

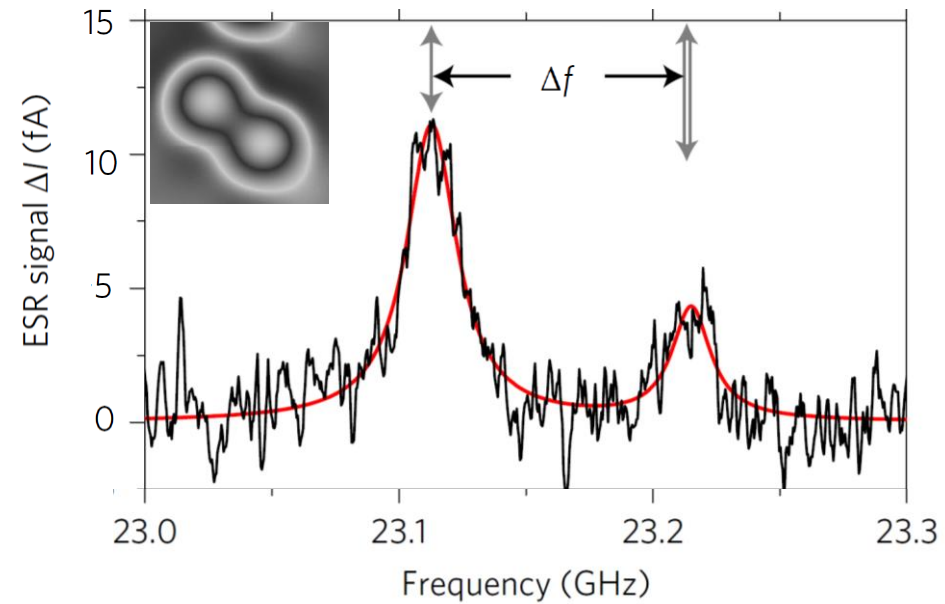
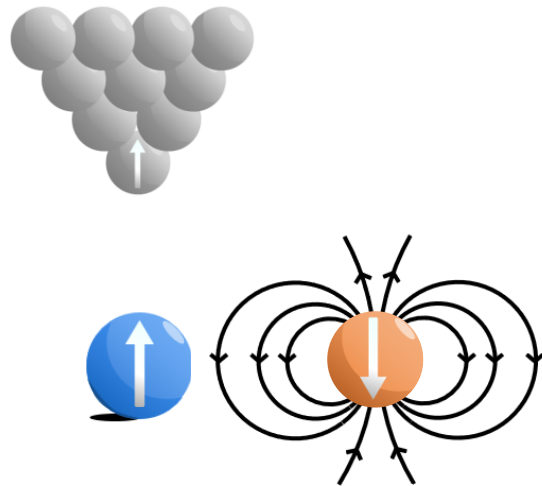
21 22 23 24 25 26 27 28 29 30

f (GHz)

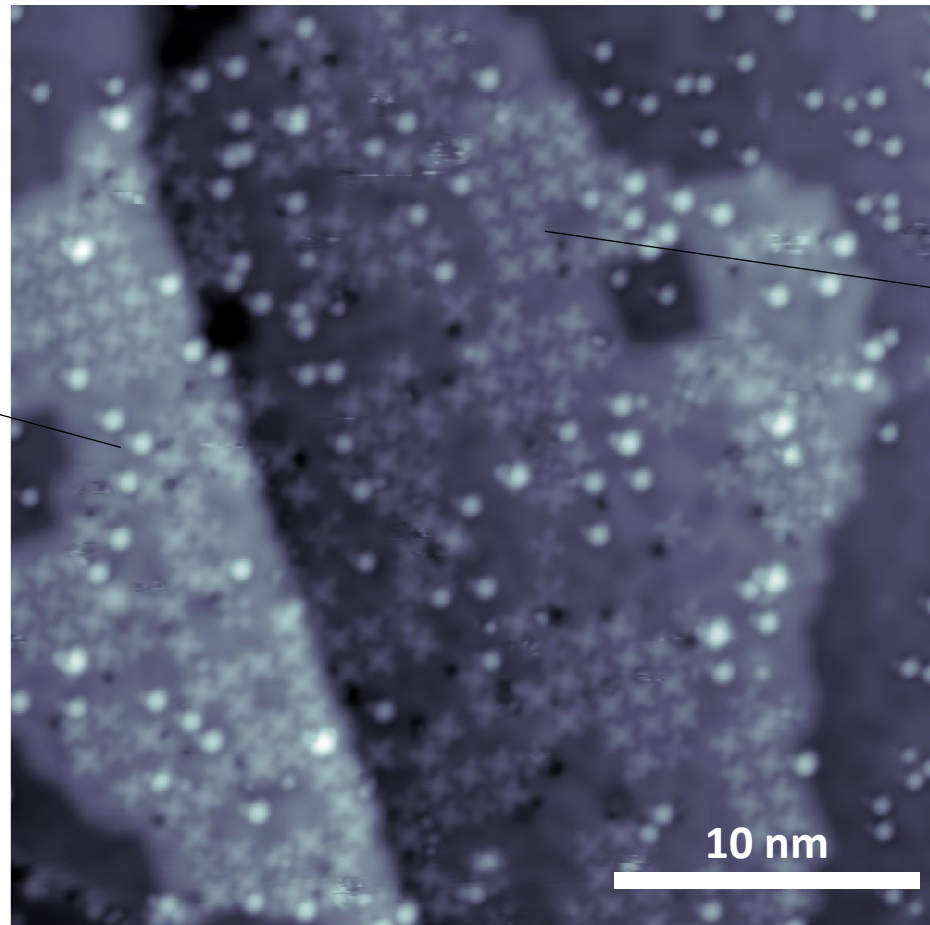
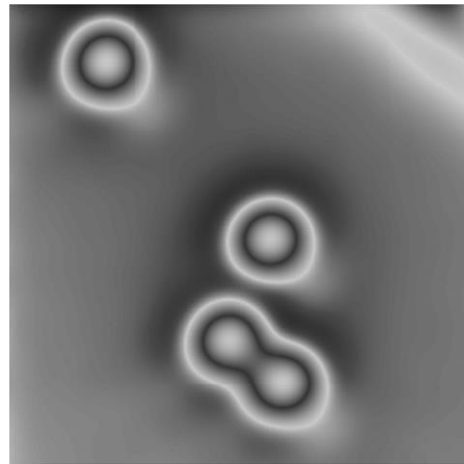


Single Atom Electron Spin Resonance

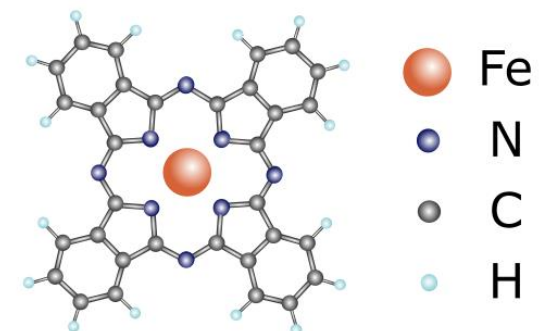
Magnetic Sensing



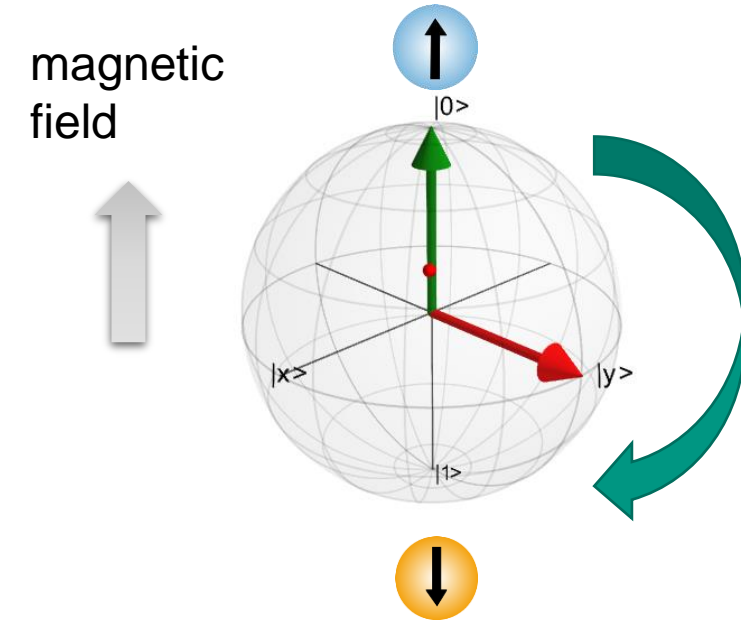
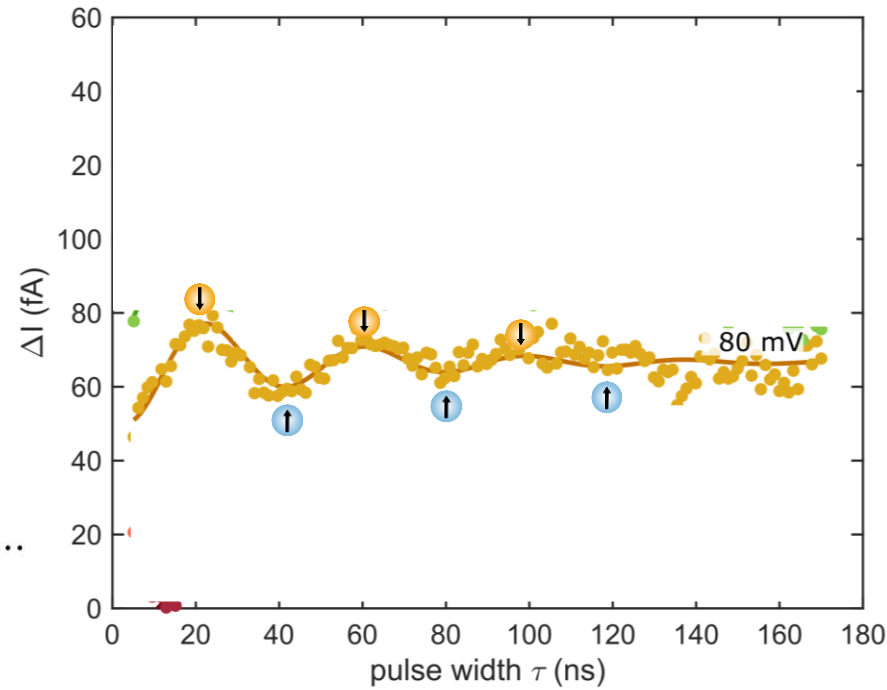
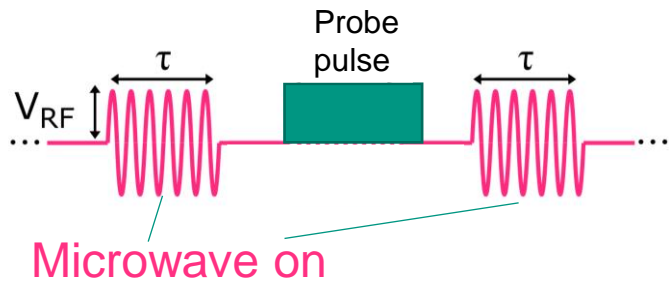
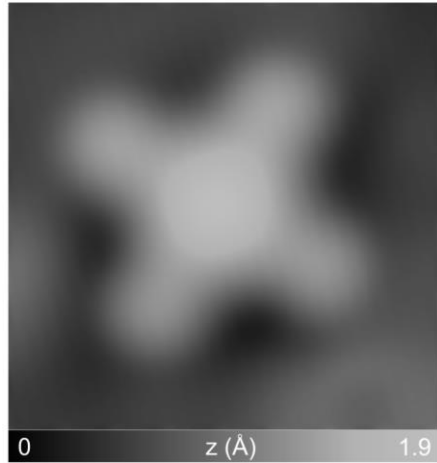
ESR on individual molecules



X. Zhang, ..., PW, et al.,
Nat. Chem. **14**, 59 (2022)



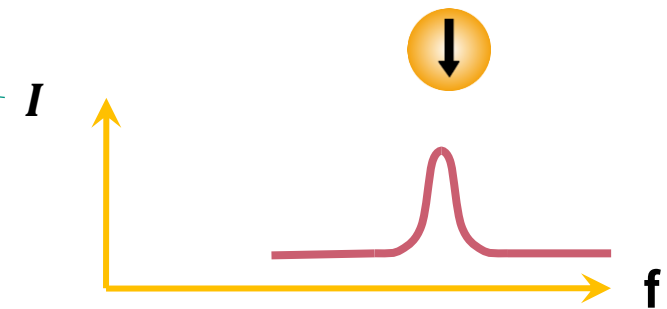
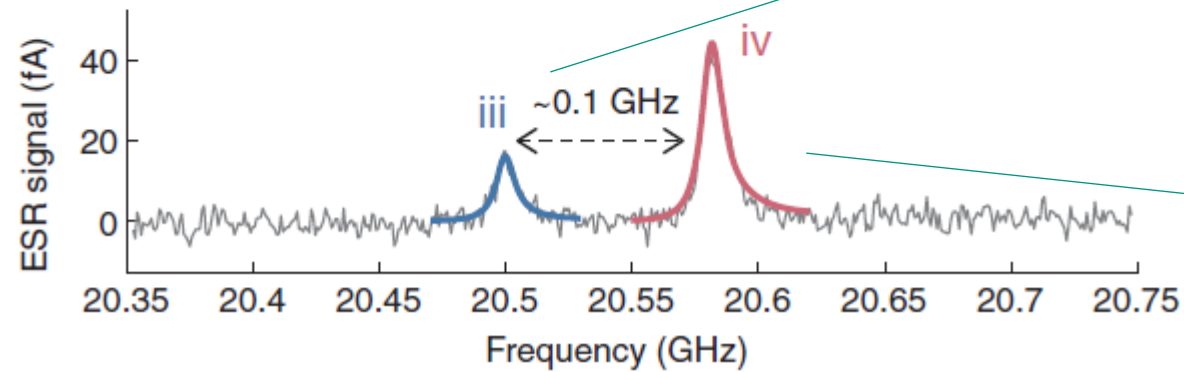
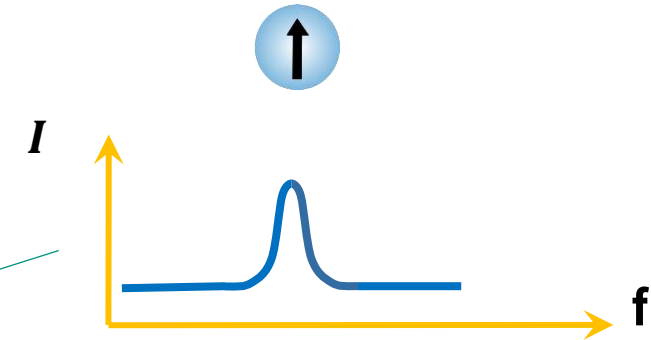
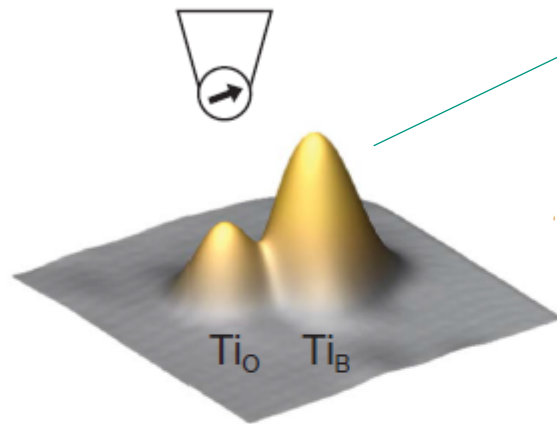
Rabi Oscillation Measurements



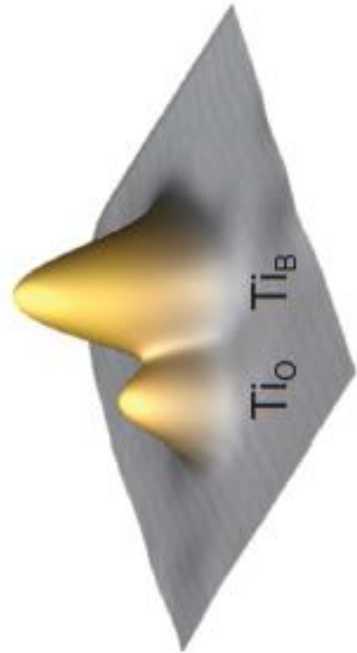
- RF voltage can rotate the spin from the ground to the excited state

Interacting spins

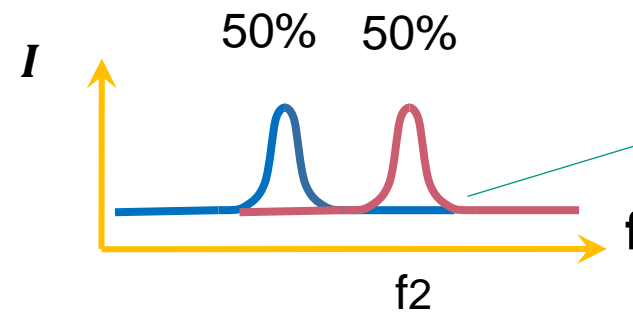
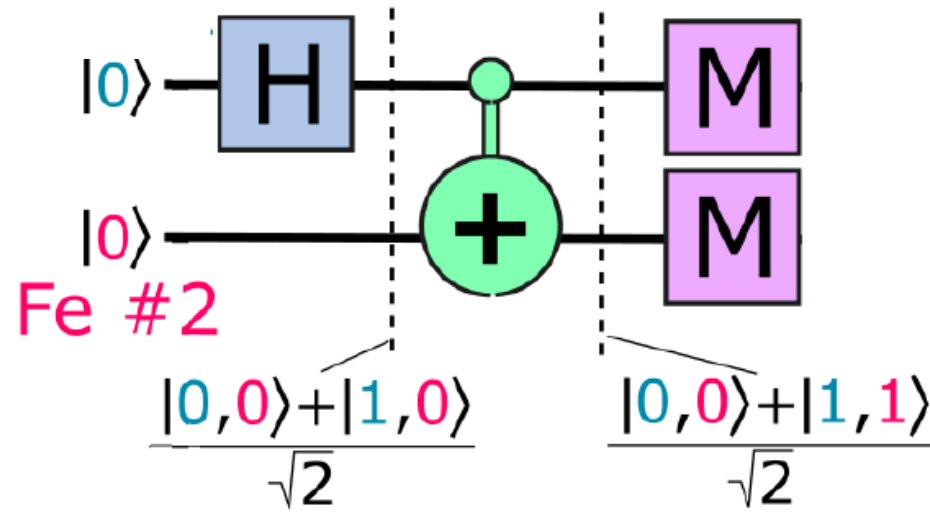
Second spin acts like a small magnet



Entanglement

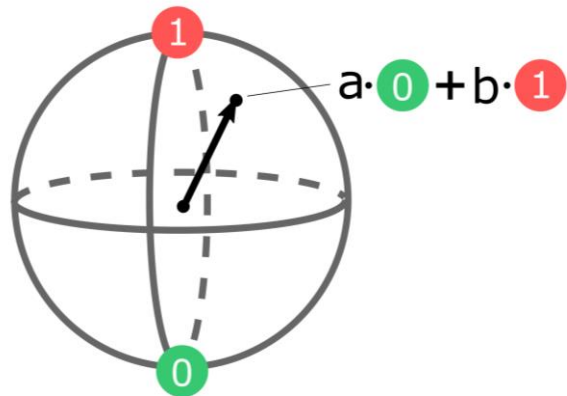


After the Hadamard, the 1st spin is in a superposition



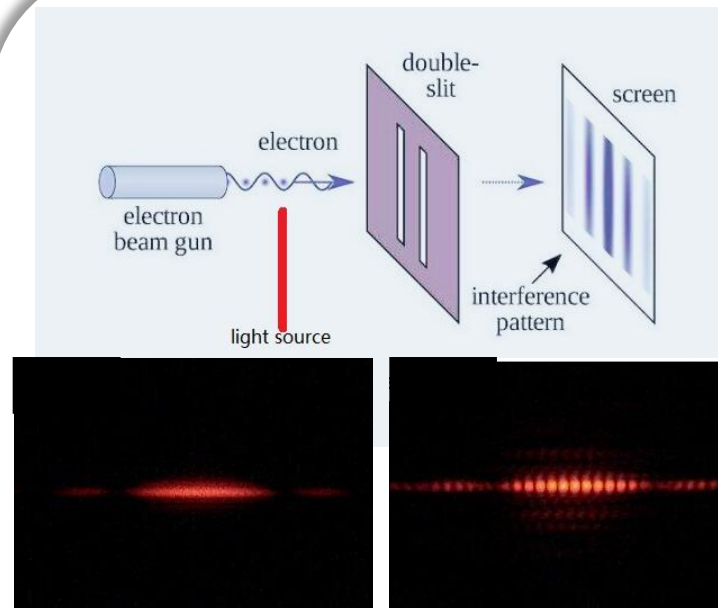
Then: pi-pulse @ f_2

■ Superposition



$$|\psi\rangle = a \cdot |0\rangle + b \cdot |1\rangle$$

■ Interference



$$\Psi_1(x,t) + \Psi_2(x,t) = 0$$

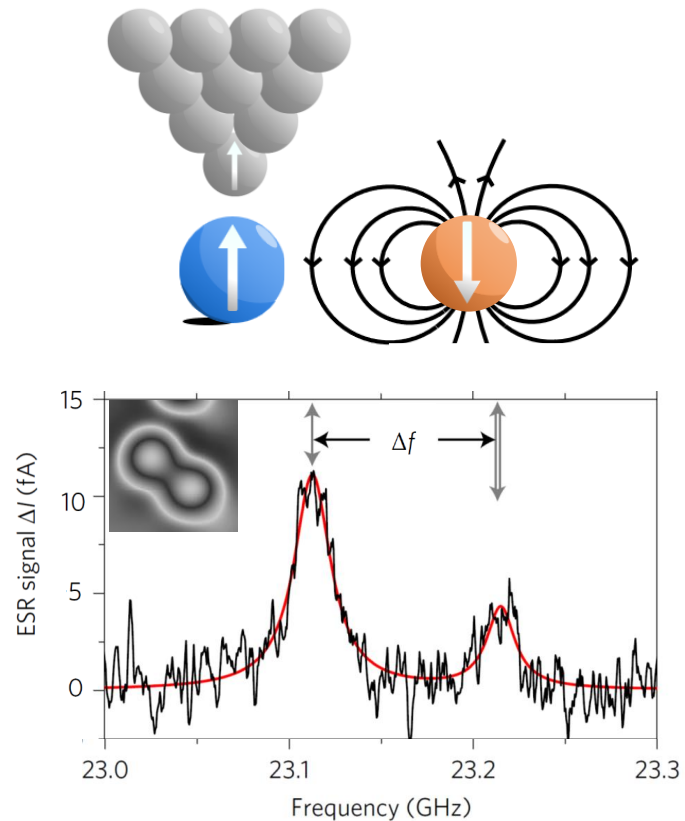
■ Entanglement



$$|\psi\rangle = |00\rangle + |11\rangle$$

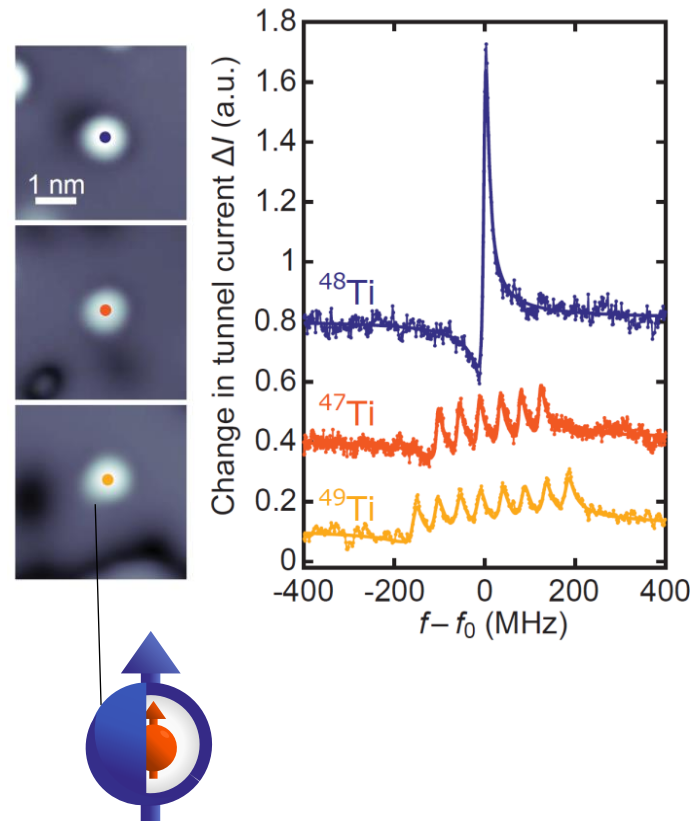
Stuff that we are good at

Magnetic Sensing



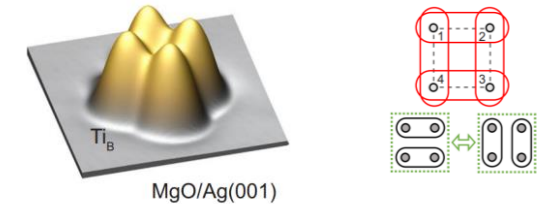
T. Choi, ..., PW et al., *Nat. Nano* **12**, 420–424 (2017)

Nuclear Spins

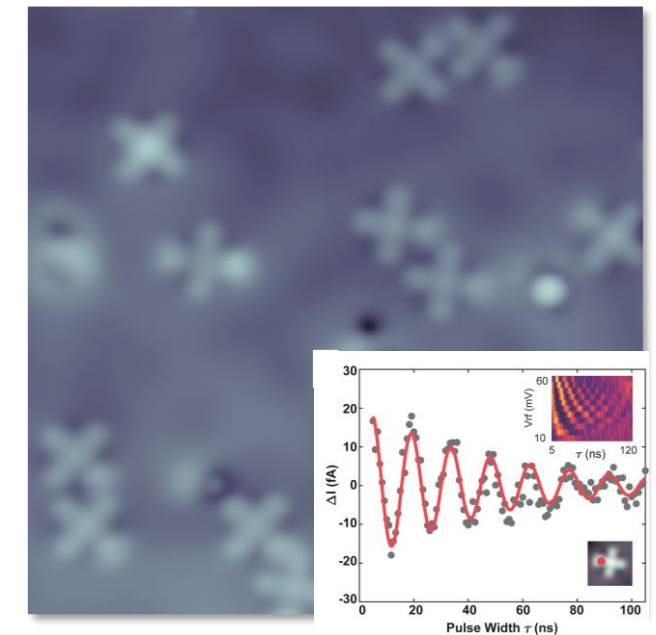


P. Willke et al., *Science* **362** (2018)

Artificial Quantum Systems

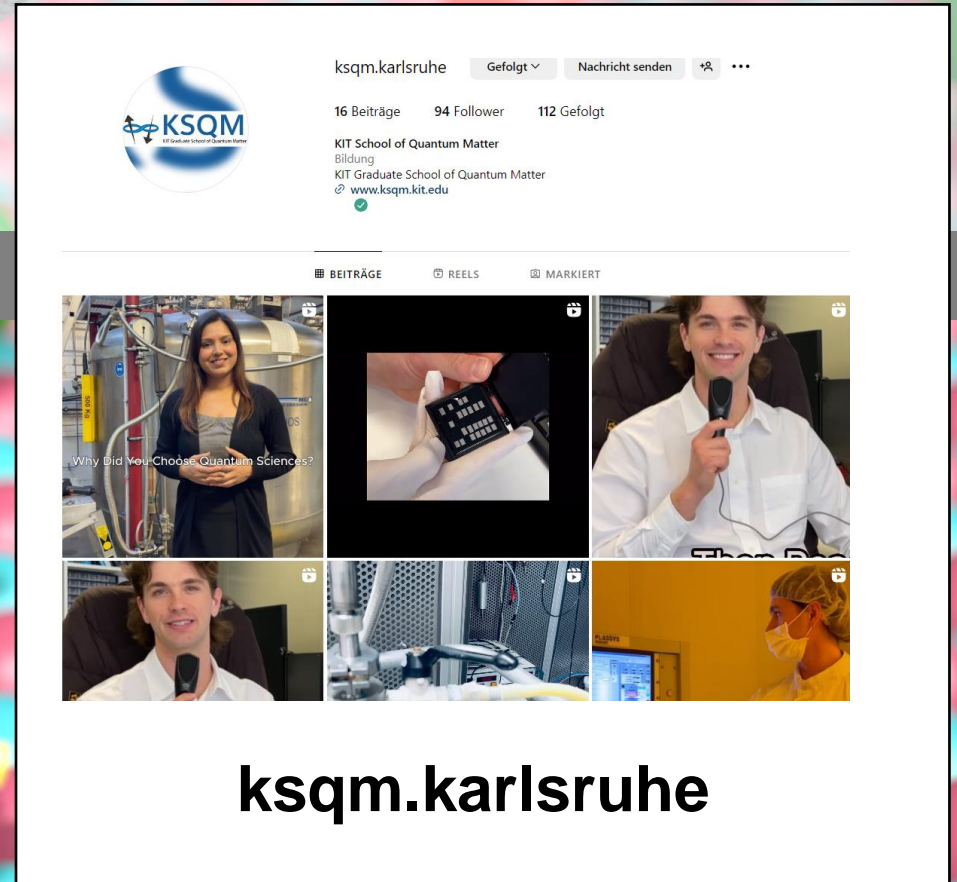


K. Yang, ... PW, et al., *Nat. Commun.* **12**, 993 (2021)



TTProf. Dr. Philip Willke | Physikalisches Institut

X: @WillkePhilip
www.atomholics.de



The screenshot shows the Instagram profile for 'ksqm.karlsruhe'. The profile picture is the KSQM logo. The bio includes 'KIT School of Quantum Matter', 'Bildung', 'KIT Graduate School of Quantum Matter', and the website 'www.ksqm.kit.edu'. The post grid features several images: a woman in a lab, a hand holding a quantum device, a man speaking into a microphone, and other lab-related scenes.

ksqm.karlsruhe Gefolgt Nachricht senden

16 Beiträge 94 Follower 112 Gefolgt

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Bildung
KIT Graduate School of Quantum Matter
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