

KIT LehrerInnenfortbildung 2024

Grundlagen
und Konzepte
von Quanten-
technologien

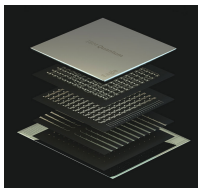
Prof. Anja Metelmann

Karlsruhe Institut of Technology & University of Strasbourg

Karlsruhe, 19. Juni 2024

(Zukünftige) Quantentechnologien

Computer



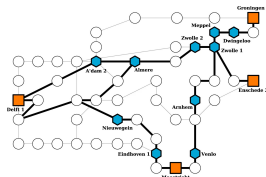
[IBM, Eagle 127 qubit chip, 2021]

Sensorik



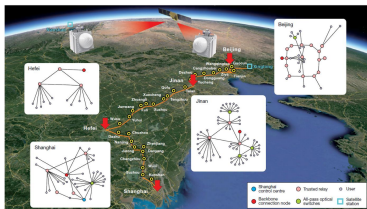
[LIGO (MIT/Caltech)]

Kommunikation



[J. Rabie et. al., npj Quantum 2022]

Verschlüsselung



[Nature 549, 70 (2017)]

'Quanteninternet'



[Bild von Prof. D. Hunger, KIT]

Was sind Quanteneffekte?

- Superposition
- Messung
- Verschränkung

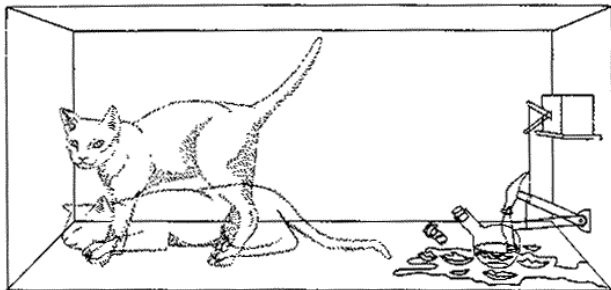
Superposition

Überlagerungszustand

$$|\Psi\rangle = \frac{1}{\sqrt{2}} \left(|0\rangle + |1\rangle \right)$$

Schrödinger's Katze

[thejoshabraham.squarepace.com]



[faraday.physics.utoronto.ca/PVB/Harrison/SchrodCat/SchrodCat.html]

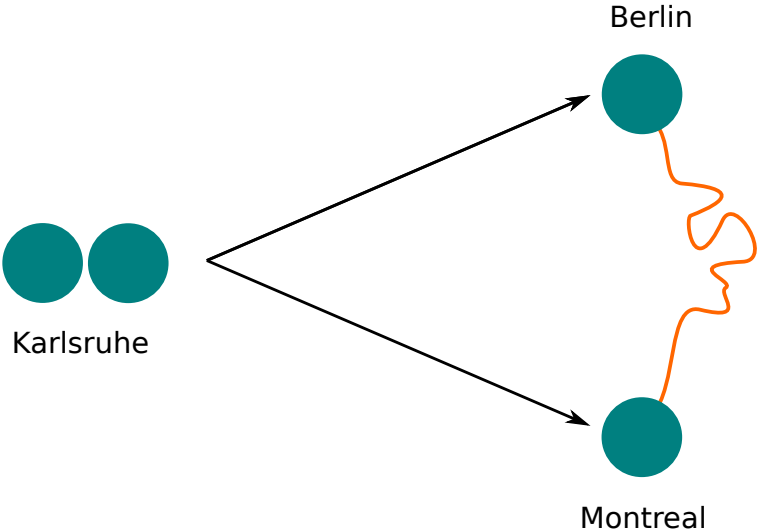
Messung

$$|\Psi\rangle = \frac{1}{\sqrt{2}} \left(|0\rangle + |1\rangle \right)$$

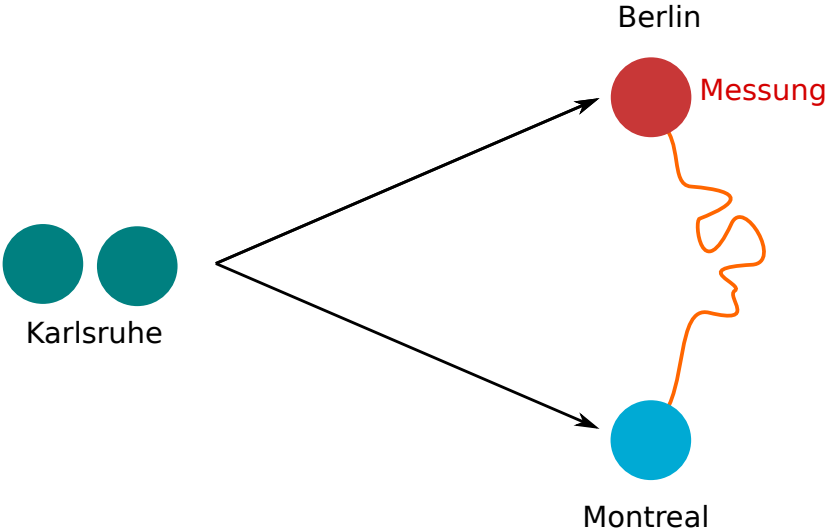

beide Messergebnisse mit je 50% Wahrscheinlichkeit

Superpositionszustand wird zerstört!

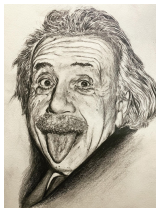
Verschränkung



Verschränkung



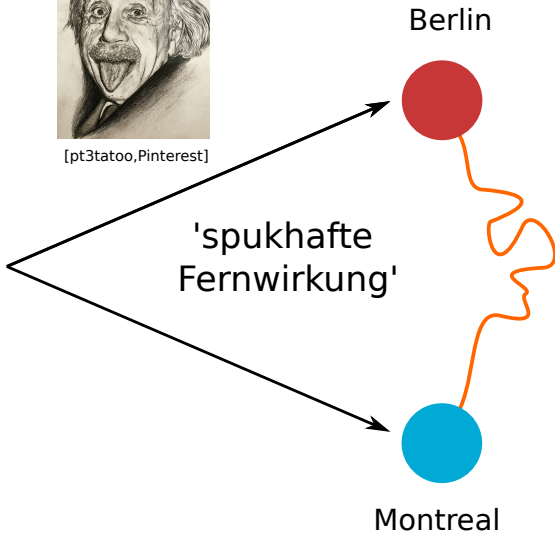
Verschränkung



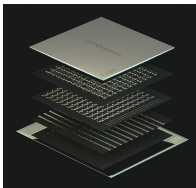
[pt3tattoo, Pinterest]



Karlsruhe



Quantencomputer



[IBM, Eagle 127 qubit chip, 2021]

Basiskomponente(n) des Quantencomputer

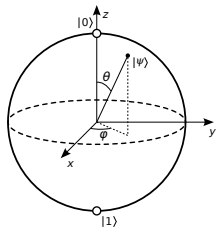
- zwei-Niveau System: Quantum Bit (Qubit)

$$\text{---} |1\rangle \quad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\text{---} |0\rangle \quad |0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Superposition:

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



- Manipulierung des Qubits: Quantengatter

$$\hat{\sigma}_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \hat{\sigma}_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \hat{\sigma}_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

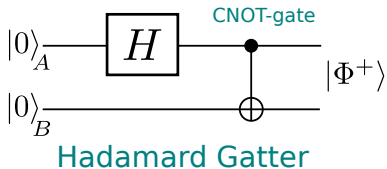
zum Beispiel: NOT - Gatter

$$\hat{\sigma}_x |0\rangle = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} = |1\rangle$$

X-Gatter
=
bit-flip

Zwei-Qubit Gatter: Beispiel verschränkte Zustände

Zustandspreparation:



$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

- Superposition des A-qubits:

$$H|0, 0\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A + |1\rangle_A) |0\rangle_B$$

- Phasen-flip Gatter (C-NOT)

(invertiert Qubit-B nur
wenn Qubit-A in 1 ist)

$$\Rightarrow \text{C-NOT } H|0, 0\rangle = |\Phi^+\rangle$$

Bell Zustände (maximal verschränkt)

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B)$$

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A \otimes |0\rangle_B - |1\rangle_A \otimes |1\rangle_B)$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |0\rangle_B)$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A \otimes |1\rangle_B - |1\rangle_A \otimes |0\rangle_B)$$

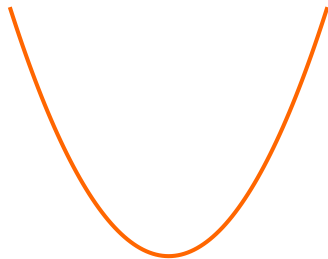
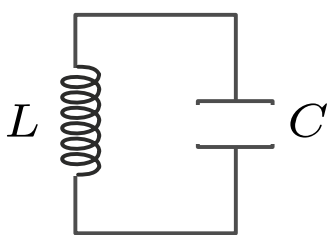
Implementierung: supraleitende Schaltkreise



Harmonischer Oszillator

$$V(X) = \frac{m}{2} \omega^2 X^2$$

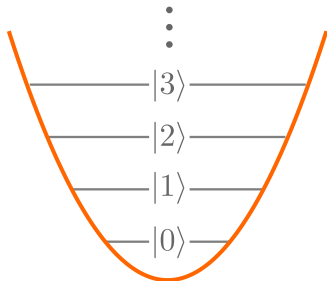
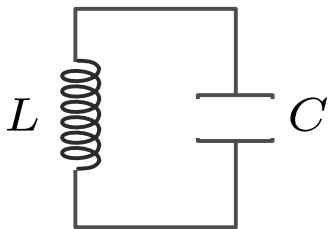
Implementierung: supraleitende Schaltkreise



Harmonischer Oszillator

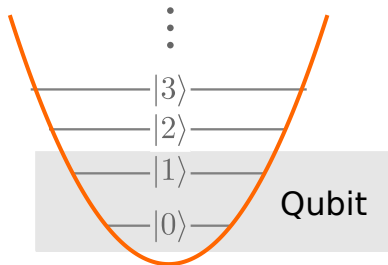
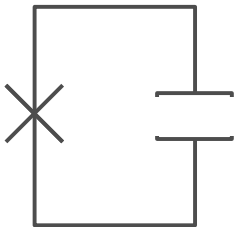
$$V(X) = \frac{m}{2} \omega^2 X^2$$

Implementierung: supraleitende Schaltkreise



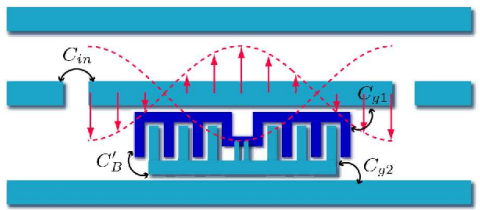
Quanten Harmonischer Oszillator

Implementierung: supraleitende Schaltkreise

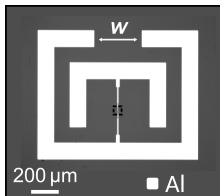


Quanten anharmonischer Oszillator

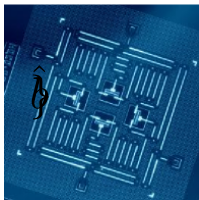
Implementierung: supraleitende Schaltkreise



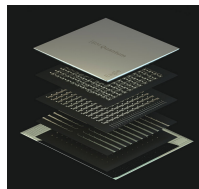
[J Koch et al., PRA 76, 042319, 2007]



[Pop, KIT, PRX 2020]



[Gambetta, npj, 2017]



[IBM, Eagle 127 qubit chip, 2021]

Quanten-Teleportation

$$|\Phi\rangle$$

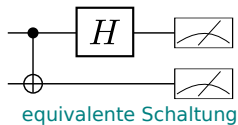
Quanten-Teleportation



- Alice & Bob erhalten Qubit eines verschränkten Paares
- Alice hat einen weiteren Qubit (C)

$$|\psi\rangle_C \otimes |\Phi^+\rangle_{AB} = (\alpha|0\rangle_C + \beta|1\rangle_C) \otimes \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B)$$

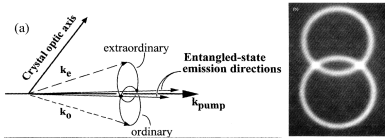
- Alice führt eine Bell-Messung durch
 \Rightarrow Alice Qubits sind in einem Bell Zustand



- Alice gibt Bob ihr Messresultat (Klass. Kommunikation)
- Bob kennt dann Zustand seines Qubits B (evtl. Lok. Op.)

\Rightarrow Zustand von Qubit C wurde zu Qubit B teleportiert

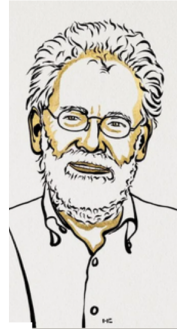
Quanten-Teleportation



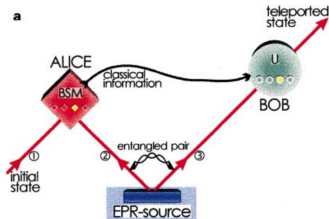
[P. G. Kwiat et al., PRL 1995]

„einfache“ Quelle
verschränkter
Photonen mit
nichtlinearer Optik

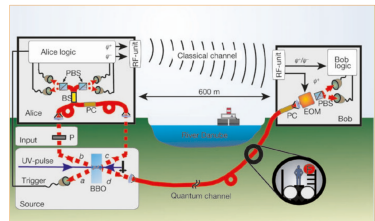
Nobelpreis 2022



Ressource für Quantenteleportations Experimente



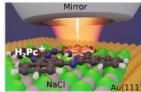
[D. Bouwmeester et al, Nature 390, (1997)]



[R. Ursin et al, Nature 430, 849 (2004)]

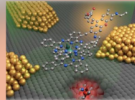
Quantentechnologien am KIT

single-molecule light emission in STM



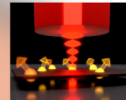
W. Wulfhekel

Quantencomputing mit Molekülspins



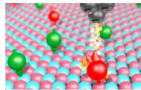
W. Wernsdorfer

Spin-Photon Schnittstellen



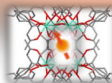
D. Hunger

single spin control in STM



P. Willke

Molekulare Quantenmaterialien



M. Ruben



P. Roesky

engineered quantum systems



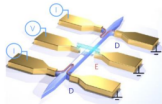
A. Metelmann

nano-optics



C. Rockstuhl

integrated opto-electronic quantum devices



R. Krupke

Supraleitende Quantenschaltkreise



I. Pop



A. Ustinov

$$\mathcal{H}_S = \mathbf{B} \cdot \mathbf{Z} \cdot \mathbf{B} + \mathbf{B} \cdot \mathbf{M} \cdot \mathbf{I} + \mathbf{I} \cdot \mathbf{Q} \cdot \mathbf{I}$$

molecular spins multi-qubit systems



K. Fink



S. Shnirman

Supraleitende Quantenmaterialien



M. Le Tacon



J. Schmalian



A. Mirlin