Superconducting qubits for analogue quantum simulation

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Experiments in Innsbruck on cQED

Quantum Simulation using cQED

\[ |\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle \]

\[ \sqrt{2} \]

Quantum Magnetomechanic

Josephson Junction array resonators
Outline

• Introduction to Circuit QED
  – Cavities
  – Qubits
  – Coupling

• Analog quantum simulation of spin models
  – 3D Transmons as Spins
  – Simulating dipolar quantum magnetism
  – First experiments
cavity QED $\rightarrow$ circuit QED

optical photons $\downarrow$

microwave photons

optical resonators $\downarrow$

microwave resonators

atoms as two level systems $\downarrow$

nonlinear quantum circuits

QIP, quantum optics, quantum measurement...

Many groups around the world:
Yale University, UC Santa Barbara, ETH Zurich, TU Delft, Princeton, University of Chicago, Chalmers, Saclay, KIT Karlsruhe...
Cavities
Waveguide microwave resonator

\[ \lambda/2 \]

Observed Q's > 10^6

Quantum Circuits

Around a resonance:

$$\hat{\Phi} \leftarrow L \quad C \rightarrow \hat{Q}$$

$$H = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L}$$

$$\hat{Q} = \sqrt{\frac{\hbar}{2Z_0}} (a + a^\dagger) \quad \hat{\Phi} = i \sqrt{\frac{\hbar Z_0}{2}} (a - a^\dagger)$$

Quantum Harmonic Oscillator

$$H = \hbar \omega_0 \left( a^\dagger a + \frac{1}{2} \right)$$

Classical drive

Energy

Energy levels:

$$|0\rangle \rightarrow |1\rangle \rightarrow |2\rangle$$

Resonance conditions:

$$Z_0 = \sqrt{\frac{L}{C}} \rightarrow 1 \ldots 100 \, \Omega$$

$$\omega_0 = \sqrt{\frac{1}{LC}} \rightarrow 4 \ldots 10 \, GHz$$
Qubits – 3D Transmon
Josephson Junction

\[ \hat{H} = -E_j \cos \phi \]

\[ \hat{H} = -E_j \cos \phi + \frac{\hat{Q}^2}{2C} \]
Superconducting Qubits - Transmon

Transmon

\[ \hat{H} = -E_j \cos \hat{\phi} + \frac{\hat{Q}^2}{2 C_\Sigma} \]

Energy

Using the same replacement rules as for the Harmonic Oscillator

\[ H = \hbar \omega_0 b^\dagger b - \frac{E_c}{2} (b^\dagger b)^2 \]

Koch et al. Phys. Rev. A 76, 042319

\[ \omega_0 = 5 - 10 \, GHz \]

\[ E_c = 300 \, MHz = \alpha \]
Transmon coupled to a Resonators

\[ H = \hbar \frac{\omega_q}{2} \sigma_z + \hbar \omega_r a^+ a \]

\[ H_{int} = \hbar g (a^+ \sigma^- + a \sigma^+) \]

\( g = 50 - 250 \text{ MHz} \)

Jaynes Cummings Hamiltonian

\[ \downarrow \]

driving, readout, interactions
Transmon - Transmon coupling

Direct capacitive qubit-qubit interaction

\[ H_{\text{int}} = \hbar J (\sigma^+ \sigma^- + \sigma^- \sigma^+) \]

\[ J = 50 - 250 \, \text{MHz} \]
3D Transmon coupled to a Resonator

Large mode volume compensated by large “Dipolemoment” of the qubit

\[ |\vec{d}| = 2e \cdot 1mm \approx 10^7 \text{Debye} \]

Observed Q’s up to 5 M \[ T_1, T_2 \leq 100 \mu s \]
Superconducting qubits for analog quantum simulation of spin models


Quantum Simulation

The problem: Simulating interacting quantum many-body systems on a classical computer is very hard.

The approach: Engineer a well controlled system that can be used as a quantum simulator for the system of interest.
The basic idea & some systems of interest...

Spin chain physics

\[ |\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle \]

\[ \frac{\sqrt{2}}{2} \]

2D spin lattice

\[ \Psi = ? \]

Open quantum systems

...spins

...interactions
Finite Element modeling - HFSS

Eigenmodes of the system:

Mode frequency (GHz) vs. $L_1$ (nH)

- $Q_1$ uncoupled
- $Q_1$ coupled
- $Q_2$
- Cavity

$2g$ and $2J$ points highlighted.

Qubit – Qubit interaction

\[ J(r, \theta_1, \theta_2) = J_0 d_m^2 \frac{\cos(\theta_1 - \theta_2) - 3 \cos \theta_1 \cos \theta_2}{r^3} + J_{cav} \]
Interaction tunability

- Qubit - Qubit angle and position
  - tailor interactions
- Qubit - Cavity angle
  - tailor readout & driving
  - measure correlations

Spin chain physics

\[ |\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle = \frac{1}{\sqrt{2}} \]
Scaling the system

- Fine grained readout
- Competition between short range dipole and long range photonic interaction
- Band engineering is possible
- Inbuilt Purcell protection
- Dissipative state engineering

Open quantum systems
To do list – theory input

• How to best **characterize** these systems?

• What do we want to **measure**?

• How do we **verify/validate** our measurements?

• How does it work in the **open system** case?
Simulating dipolar quantum magnetism

*Phys. Rev. B 92, 174507 (2015)*
Model to simulate

**XY model on a ladder**: Superfluid and Dimer phase

**Analogue Quantum Simulation with Superconducting qubits**

\[
H = \sum_{i,j} J \left( \frac{\theta_1, \theta_2}{|r_{i,j}|^3} \right) (S_i^+ S_j^- + \text{h. c.}) + \sum_i h_j S_i^z
\]

In Collaboration with M. Dalmonte & D. Marcos & P. Zoller
Static properties of the model

Order parameter and Bond Correlation

Disorder influence on the Bond Correlation

Bond order parameter shows formation of triplets for $J_2/J_1 = 0.5$

\[
D^\alpha = \left( \sum_{j=1}^{L-1} D_j^\alpha \right)
\]

\[
D_j^\alpha = (-1)^j S_j^\alpha S_{j+1}^\alpha \quad \alpha = x, z
\]

\[
B^z = D_{L/2}^z
\]
Adiabatic state preparation

System size: $L = 6$, $2J_2 = J_1 = 2\pi \cdot 100$ MHz,

Including disorder $\delta h/J_1 = 0.25$
Experimental progress
Experimental progress - Qubits

✓ Single qubit control, frequency tunable

\[ T_1 \approx 40 \, \mu s, \; T_2 \leq 25 \, \mu s \]
Experimental progress - Qubits

✓ Multiple qubits and interactions

\[ H_{\text{int}} = \hbar J (\sigma^+ \sigma^- + \sigma^- \sigma^+) \]

\[ J \approx 70 \text{ MHz} \]
Qubit measurements & state preparation

• During the simulation:
  \[ \omega_i = \omega_j \quad \forall \ i, j \]

• We want to measure:
  \[ \sigma_i^m \otimes \sigma_j^m \]

• We want to be able to bring excitations into the system

⇒ fast flux tunability necessary
Tuning fields with a Magnetic Hose

- Transport B-field from A to B

Diamagnet: $\mu_r^\perp = 0$

Ferromagnet: $\mu_r^\parallel < \infty$

Long-distance Transfer and Routing of Static Magnetic Fields
Experimental progress - Magnetic Hose

\[ T_1 \geq 15 \, \mu s \]

Purcell limited

\[ T_2 < 15 \, \mu s \]

depends on flux bias
Experimental progress - Magnetic Hose

- Flux pulse
- \( \pi \) pulse
- Readout

50 ns pulse

Not perfectly compensated

- \( T_{\text{rise}} < 50 \text{ ns} \)
High Q Stripline resonators for waveguides
Experimental progress - Waveguides

Waveguides with resonators and qubits
Conclusion

• Circuit QED

\[ C_c \]

\[ L_r \]

\[ C_q \]

\[ C_r \]

\[ E_j \]

• 3D Transmons behave like dipoles

• Simulate models on 1D and 2D lattices

• Work in progress
Quantum Circuits Group Innsbruck – April 2017
Quantum Circuits

Around a resonance:

\[ H = \frac{\hat{Q}^2}{2 C} + \frac{\hat{\Phi}^2}{2 L} \]

Lagrangian \[ \rightarrow \]

\[ H = \frac{\hat{p}^2}{2 m} + \frac{m \omega^2 \hat{x}^2}{2} \]

energy in magnetic field \[ \leftrightarrow \] potential energy

energy in electric field \[ \leftrightarrow \] kinetic energy
Resonators and Cavities

Coplanar Waveguide Resonators

Microwaves in

10 μm

Length ~ λ/2

Ground Plane

out
Why interfaces matter... dirt happens

“participation ratio” = fraction of energy stored in material

even a thin (few nanometer) surface layer
will store ≈ 1/1000 of the energy

If surface loss tangent is poor (\(\tan\delta \approx 10^{-2}\)) would limit \(Q \approx 10^5\)

Increase spacing

\[\text{decreases energy on surfaces} \quad \Rightarrow\]

\[\text{increases } Q\]

as shown in:

Gao et al. 2008 (Caltech)
O’Connell et al. 2008 (UCSB)
Wang et al. 2009 (UCSB)

tech. solution:
Bruno et al. 2015 (Delft)
Circuit model explanation
Josephson Junction

Superconductor (Al)

Insulating barrier

1 nm

Superconductor (Al)

\[ |\Psi_A\rangle \quad \text{Superconductor (Al)} \]

\[ |\Psi_B\rangle \quad \text{Superconductor (Al)} \]

Josephson relations:

\[ I(\varphi) = I_c \sin \varphi \quad \dot{\varphi} = \frac{2e}{\hbar} V(t) \]

Regular inductance

\[ V_L = L \dot{I} \]

\[ E = \frac{\Phi^2}{2L} \]

Josephson Junction

\[ V_{jj} = \frac{\hbar}{2e I_c \cos \varphi} \dot{I} \]

\[ E = -E_j \cos(\varphi) \approx E_j \frac{\varphi^2}{2} - E_j \frac{\varphi^4}{12} + \cdots \]

\[ \varphi = \frac{2e}{\hbar} \Phi = 2\pi \frac{\Phi}{\Phi_0} \]
Josephson Junction

Junction fabrication:
- thin film deposition
- Shadow bridge technique
Charge Qubit Coherence

- Sweet Spot (Saclay, Yale)
- Charge Echo (NEC)
- Nakamura (NEC)
- Transmon (Yale, ETH)
- 3D Transmon (Yale, IBM, Delft)
- 3D Fluxonium (Yale)
- Improved 3D Transmon (Yale, IBM, Delft)

Kohärenz Zeit (ns)

# Operationen

Jahr