Sievert Lecture Series: The Rise of Quantum Machines

Lecture III: Creation of Quantum Systems by Design

Xinyuan You
Fermi National Accelerator Laboratory
From 1\textsuperscript{st} to 2\textsuperscript{nd} quantum revolutions

- First quantum revolution
  - Make use of systems with quantum properties
  - Examples: laser and transistor

- Second quantum revolution
  - Design and manipulate individual quantum systems

- Goals
  - Understand and test quantum theories
  - Explore new quantum phenomena
  - Develop novel technologies

“… nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.”

Creation of quantum systems by design

- Matter
  - Bose–Einstein condensate (Nobel Prize 2001)

- Matter + Light
  - Cavity QED (Nobel Prize 2012)
  - Circuit QED (Nobel Prize ?)
The fifth state of matter

Three states of matter in daily life:
• Gas
• Liquid
• Solid

Ultra hot state: Plasma

Ultra cold state: Bose—Einstein condensate (BEC)
Prediction of Bose–Einstein condensate (1924)

- Longer wavelength at lower temperature
- Below critical temperature (nanokelvin), particles start to overlap and behave as one single entity
How to reach the coldest place in the universe?

- Prepare lots of identical atoms, e.g., sodium, rubidium
- Laser cooling to millikelvin
- Evaporate cooling further to nanokelvin
"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"
Observation of Bose–Einstein condensates in an Earth-orbiting research lab

David C. Aveline, Jason R. Williams, Ethan R. Elliott, Chelsea Dutenhoffer, James R. Kellogg, James M. Kohel, Norman E. Lay, Kamal Oudrhiri, Robert F. Shotwell, Nan Yu & Robert J. Thompson
Applications of BEC

Atomic laser

Like laser, with photons replaced by atoms

Atomic clock

Better accuracy as all atoms behave collectively

Cavity QED: light–matter interaction

The Nobel Prize in Physics 2012

Haroche: trap photons and then probe with atoms

Wineland: trap atoms and then probe with photons
Main challenges

• How to trap photons/atoms?

• How to measure photons/atoms without destroying them?
Haroche’s approach

- Photons are trapped in a two-mirror cavity
- Frequency of atom is shifted by light
- The photons survived after the measurement

Wineland’s approach

• Charged atoms are trapped with electric fields

• Spectral information of the target ion is transferred via shared motion to a readout ion

• The target ion is intact after the measurement

Applications: quantum computing based on natural atoms

Trapped ion quantum computing

Neutral atom quantum computing

Basic elements of superconducting circuits

- No dissipation due to superconductivity
- Linear elements: capacitor, inductor
- Nonlinear element: Josephson junction

Zoo of superconducting circuits


From cavity QED to circuit QED

Cavity QED
- Natural atoms interacting with EM field in cavity
- Long lifetime but small interaction

Circuit QED
- Artificial atoms interacting with EM field in resonator
- Short lifetime but large interaction
Applications: quantum computing based on artificial atoms

IBM 5-qubit processor (2015)

IBM Ospery 433 qubits (2022)

Rigetti dilution refrigerator
Lecture III: Creation of quantum systems by design

- Creation of Bose—Einstein condensate
- Manipulate light interaction with natural and artificial atoms