Superconducting Flux Qubits: The state of the field

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Outline

• A brief introduction to the Superconducting Flux Qubit

• Current research topics in the field
  LTS qubits
  HTS qubits
  Coupling qubits
  Qubits in boxes
  Adiabatic Quantum Computing

• Qubit measurement
  Sources of decoherence

• Our potential role in the field
The phase is a quantum variable in a Josephson Junction qubit.

When made into a loop, phase across the junction can be controlled by the flux threading the loop.

Thus you can control the quantum variable using a macroscopic, classical variable.

THAT'S why qubits are COOL.

Example: Energy of the 3JJ Qubit:

\[ U = E_J [2 + \alpha - 2 \cos \phi_p \cos \phi_m - \alpha \cos (2\pi f + 2\phi_m)] \]

\[ f = \Phi / \Phi_0 \]

\[ \phi_p = (\phi_1 + \phi_2) / 2 \]

\[ \phi_m = (\phi_1 - \phi_2) / 2 \]

Common to all qubits: Some way of establishing either a double well potential or a two level quantum system.

Qubit energy as a function of phase across each junction

Mooij et al. Science 245 (1999)
Meet the family

The SCFQ family

- RF SQUID
- CJJ
- 3JJ
- DD-DD 'Silent'
- SIS + π SD 'Quiet'
- RF π SQUID
- 4JJ
- 3JJ + SQUID
- 5JJ 'Quiet'
- 3JJ + SQUID

Why 3 Junctions? Josephson Junctions add an inductance term, so you don't need a large loop.

Why 4 Junctions? Allows modulation of the barrier between the double wells – an extra control (similar to CJJ)

Why π Junctions? Easy to obtain a degenerate ground state - the double well potential occurs intrinsically at zero applied flux bias

Example of a qubit:
The Delft 3JJ device - (scale bar is 1um)

Can you think of more?

Also:
Current biased junction (pure phase)
Current qubit technology
LTS Qubits

The modern design of the Superconducting Flux Qubit (SCFQ) is nearly 10 years old.

**Mooij et al. Science 245 (1999)**

The first successful measurement of quantum coherent oscillations in an Aluminium qubit device was shown in 2003:

**Chiorescu et al., Science 2003, Vol. 299. no. 5614**

Niobium and Aluminium based systems are still the most promising technology for qubit production. Aluminium is cleaner, but more difficult to check characteristics $T_c(\text{Al}) \approx 0.3 \text{K}$ $T_c(\text{Nb}) \approx 9.1 \text{K}$.

Most current fabrication facilities have a Niobium trilayer process, (usually as a result of RSFQ research). Niobium is a therefore a standard technology.

The most advanced types of qubit circuits currently under test are made using these Nb /NbOx / Nb trilayer junctions

**Van der Wal et al., Science 290, 2000**

**Friedman et al., Nature 406, 2000**
HTS Qubits

Amin et al. concentrated on tilt Grain boundary junctions (theoretically).
Chalmers group concentrated on 'twist' grain boundary junctions (experimentally).

**Bauch et al., Science 311, (2006)**

They did not measure $T_2$ (decoherence time) directly but looked at the Q value of excitations between $|0\rangle$ and $|1\rangle$ states.

There has also been a lot of work on the quantum properties of Intrinsic Junctions (e.g. In BSCCO), but no-one has made a qubit from this yet.

Most people believe that HTS will never make good qubits, due to high decoherence, even though these silent designs have been tested to some extent.
Coupling qubits

With two coupled qubits you can make a CNOT gate!


Grajcar et al., PRL 96 (2006)
A superconducting Coplanar Waveguide Resonator stores energy in the form of microwave photons 'in a box'.

Place a qubit nearby -> there will be an interaction between the energy levels of the qubit and those of the resonator when they are tuned to operate at the same frequency.

**Advantage** – frequencies other than the resonant frequency are attenuated by the cavity

**Drawback** – not very scalable


Several groups working in this area:

**Martinis group**  
Tune the qubits in and out of resonance with a fixed resonator and measure the qubits

**Schoelkopf group**  
Keep the qubits' frequencies fixed and adjust the resonator (an alternate method).

Demonstration of 2 qubits in a resonator (physically a few mm apart) swapping quantum state information

**Saclay group / Chalmers group**  
Putting a Josephson Inductance (SQUID) at one end of the resonator allows the resonant frequency of the CPW to be adjusted by application of a flux to the SQUID. They also keep the qubits fixed.

**Wallraff (Zurich) group**  
Adiabatic Quantum Computing (AQC)

A different (top down) approach to using qubits for quantum computing
So far the methods discussed transfer quantum information between qubits, or gates

AQC works like simulated annealing - make a large array of qubits, coupled to their nearest neighbours, and solve problems by finding the minimum energy of the entire system.

**D-Wave systems** are working on this method:

An array of 16 qubits, each coupled to their nearest neighbours.

Each individual qubit is a Composite Josephson Junction (tunable flux qubit). They are coupled together in blocks using RF-SQUID couplings.

**Harris et al., PRL 98, (2007)**

This is the most advanced qubit coupling scheme implemented by anyone so far. However with a 'top-down' approach... Is it truly quantum?
Qubit measurement
Qubit measurements - an example

E.g. For a Phase qubit:

1.) Apply flux bias pulse to initialise states
2.) Apply flux bias to generate 2 levels in the well
3.) Apply microwave flux pulse to excite superposition
4.) Lower barrier so that high probability of $|1\rangle$ tunneling if occupied
5.) Raise barrier -> 'freeze' qubit state
6.) Measure state with DC SQUID readout

McDermott et al., Science 307 (2005)
Qubit measurements

Rabi oscillations

Repeat process stochastically -> Time domain coherence measurements (Rabi oscillations) by varying the length of the microwave pulse.

Rabi oscillations demonstrate quantum coherent rotations around the Bloch sphere, i.e. a driven evolution of the superposition of states.

Chiorescu et al., Science 2003, Vol. 299. no. 5614

There are many groups who have already demonstrated MQC in many different junction systems

We are hoping to find quantum coherent properties in novel junctions and investigate further the decoherence mechanisms in such devices.

We are currently in process of setting up a system to measure $T_1$, $T_2$, etc. and see Rabi oscillations
The remaining major cause of decoherence is believed to be two level systems in the dielectric.

Intrinsic to the junction -> The qubits are now limited by the materials technologies.

**Simmonds et al., PRL 93 (2004)**

Spurious TLS are bad for your qubit!

There are some other possibilities - trapped flux near the edges? Perhaps investigating edge profiles may be interesting.

Niobium Nitride Junction technologies are being developed - this may help reduce TLS.

**Martinis et al., PRL 95 (2005)**

Dielectric matters!
Our role in the research?
Novel Junctions

**Ramp junctions**
S-wave/D-wave hybrid junctions - Intrinsic pi phase shift included in SQUID loop.
Chesca et al., PRB 73 014529 (2006)

**Ferromagnetic junctions**
In collaboration with Cambridge we are also investigating pi-phase shift LTS junctions
Robinson et al., PRL 97 (2006)

**Phase slip systems - HTS / LTS**
Evidence of Phase Slip processes in narrow tracks in YBCO.
Mooij et al., New J. Phys. 7 (2005) 219 'Phase slip qubits'

YBCO junctions can be defined by Focussed Ion Beam milling
Qubit and resonator

Circuit QED with a flux qubit strongly coupled to a coplanar transmission line resonator

Magnetic field tuning of coplanar waveguide resonators due to flux focusing
http://arxiv.org/abs/0805.2818

Ultimate goal -> Combine the resonator and qubit projects
Collaborations....?

- A fabrication facility such as IPHT are able to make Niobium tunnel junctions and other circuit elements with good reproducibility and scalability. We can use such a facility to produce more complicated qubit circuits, including coupled qubits. They also have a facility for making Aluminium junctions.

- Take advantage of the European Fluxonics Foundry for more extensive qubit circuitry and expertise in the field (e.g. the CNR-Roma/Karlsruhe collaboration)

- In the short term, Cambridge can make Niobium Junctions and small qubit circuits to our specification.

- Investigate other types of junction (e.g. Niobium Nitride) - e.g. Made by J. C. Villagier at CEA Grenoble

- Theory group at Birmingham may be interested in microwave activation / decoherence studies / the use of the second harmonic in unconventional junctions
Conclusion

- The field of Superconducting Flux Qubits is active and extremely varied. There are many groups around the world working in this field and lots of potential collaborations.

- We are taking the first steps towards coherent quantum measurements in a range of systems.

- Niobium technology is extremely far ahead, however there is a niche in MQC measurements in novel junction systems.

- We should also continue with fundamental research into different types of junctions, in order to isolate potential areas to improve on the existing junction technologies. SD / SFS / Niobium Nitride??

- New measurements will investigate how novel junctions differ from the ideal in terms of noise, mechanisms of decoherence, and potential operating range. Understand the limitations of Niobium, and perhaps suggest improvements on this technology.

- The combination of novel junction system with resonator techniques is also an unexplored area
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Thank you for your attention!
Any questions?

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