Quantum logic operations in $^{40}$Ca and $^{43}$Ca$^{+}$ trapped-ion qubits

### Mixed Species Experiment

**Goals**
- Two ion entanglement using a geometric phase gate
- High-fidelity laser gates
- Classical AND gate by controlled relaxation (useful for practical error correction schemes)

**Details**
- Qubit stored in ground state manifold ($T_1$ very large)
- Only one set of lasers needed as isotope shifts can be spanned with EOMs
- RF ($^{40}$Ca) and microwaves ($^{43}$Ca) used for single-qubit rotations
- Isotope shift of ~1 GHz allows individual addressing of the different isotopes and sympathetic cooling
- Simultaneous readout of both isotopes implemented

### 43Ca$^{+}$ Field–Insensitive Qubit

- Intermediate-field clock qubits preferable to zero-field clock qubit as Zeeman shift lifts state degeneracies
- Until now intermediate-field states only demonstrated in $^{40}$Ca and $^{43}$Ca$^{+}$ (NIST)
- $^{43}$Ca$^{+}$ has the following advantages:
  - No UV lasers which can change up the trap
  - Laser dipoles available at all required wavelengths
  - D-states for electron shielding (high웠로 쿨링)
  - However there is no closed cooling transition (see below)

**State preparation**

The ion is initialised in $F=4$,$M_F=4$ by several cycles of optical pumping and microwave ‘remapping’ pulses, giving good state preparation with impure optical polaronisation. 3 microwave pulses (green) are then used to prepare the ‘clock’ qubit (red).

**Doppler Cooling at 146G**

- $S_u$-$P_u$-$D_u$ system has 64 states and no closed transitions.
- Optical Bloch equations used to simulate the system.
- Straightforward cooling solution found:
  - Polarizations chosen so that only a few states populated
  - Needs only one sideband on cooling laser (from EOM)
  - Single frequency 866nm repumping laser
  - $P_u$ level population of up to ~0.15 simulated and achieved (50000 s$^{-1}$ total)

**Towards Microwave-driven Entanglement**

Proposed (2008) and demonstrated (Nature 471, 155, 2011) byospelkaus and coworkers at NIST.

Gate driven by oscillating microwave, rather than optical, field gradient. Ion is trapped in the near-field ~100μm from a microwave conductor to obtain high enough gradients.

**Advantages**
- Microwave electronics more mature and scalable technology than lasers
- No photon scattering as in laser-driven Raman gates
- No requirement for sub-Doppler cooling

**Disadvantages**
- Microwave field not as well localised as laser field (cross-talk)
- Careful nulling of microwave field at ion to suppress AC Zeeman shifts
- Fast gates (~10μs) will require small traps and high microwave current densities

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**The Ion Trap**

- Macroscopic linear Paul trap (RF applied to ‘blades’ (blue) for radial confinement, DC applied to “end-caps” (red) for axial confinement)
- ‘Innsbruck’ style stainless steel ‘blade’ type
- Ion-electrode distance 0.5 mm
- Typical trap parameters:
  - Trap RF drive: 30 MHz
  - Axial secular frequency: 2 MHz
  - Radial secular frequency: 4 MHz

**Cooling Results**

- Doppler cooling to $m_F < 6$
- Pulsed sideband cooling of crystal’s two axial modes to $m_F < 0.1$
- Heating rate ~5 quanta/s at $f = 2$ MHz
- Mixed crystal sympathetic Doppler cooling

**Readout**

**Trapped-ion qubits**

**Trap Design**

Trap is gold on sapphire for good thermal conductivity. The trap region is in the centre of a half-wave microwave resonator to increase currents. Quarter-wave coupling sections provide a good 50Ω impedance match.

**Towards Microwave-driven Entanglement**

Network analyser data shows that >75% of input microwave power is coupled into the trap.

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**Raman Laser System**

- Pair of injection-locked frequency-doubled amplified diode lasers gives up to 40 mW at 397 nm in each Raman beam.
- Photon scattering error for single qubit rotation predicted to be ~10$^{-7}$ at $D_u = 2n = 500$ kHz.
- System can be switched between addressing $^{40}$Ca and $^{43}$Ca in 100μs by switching injection path.
- Beat-note between Raman beams at ions sub-Hertz width

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**Comparison of experiment and theory for a frequency scan of the 866nm repumping laser**

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- Optical Bloch equations used to simulate the system.
- Straightforward cooling solution found:
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