K Thirumalai, L J Stephenson, D P Nadlinger, V M Schäfer, T G Ballance, C J Ballance, A M Steane, D M Lucas

UNIVERSITY OF OXFORD

Development of a Photonically Linked Ion Trap Network

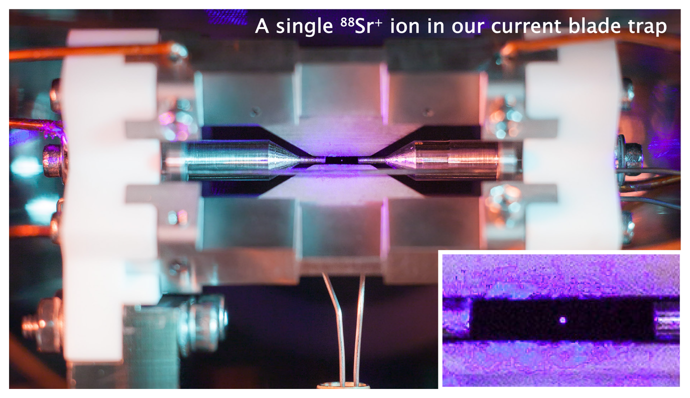
Ion Trap Quantum Computing Group
Department of Physics, University of Oxford

A promising approach to scale both quantum communication and quantum computing into useful technologies is to use many similar ion trap nodes connected together in a modular network. Raw entanglement between ions in separate nodes, created by interfering and measuring the photons they emit, can be purified using local operations in each node, to generate high fidelity entanglement distributed across the network.

Using two different ion species, $^{43}Ca^+$ as a high fidelity logic qubit for operations within each node, and $^{88}Sr^+$ to create photonic connections between them, allows one to harness the advantages of each species for both tasks without a trade-off.

Here we present initial work showing ion-photon entanglement created using a picosecond laser to repeatedly cause a $^{88}Sr^+$ ion to emit photons to which it is entangled. We also show a mixed species qubit-frequency independent, two-qubit gate between $^{43}Ca^+$ & $^{88}Sr^+$, an important component of our entanglement purification scheme.

As a demonstration of this scheme, we further report progress towards two ion traps in separate vacuum chambers with optimised photon collection for this scalable architecture. Along with compact rack-mounted laser systems for each ion species, we hope to create a pair of nodes for a future quantum network.

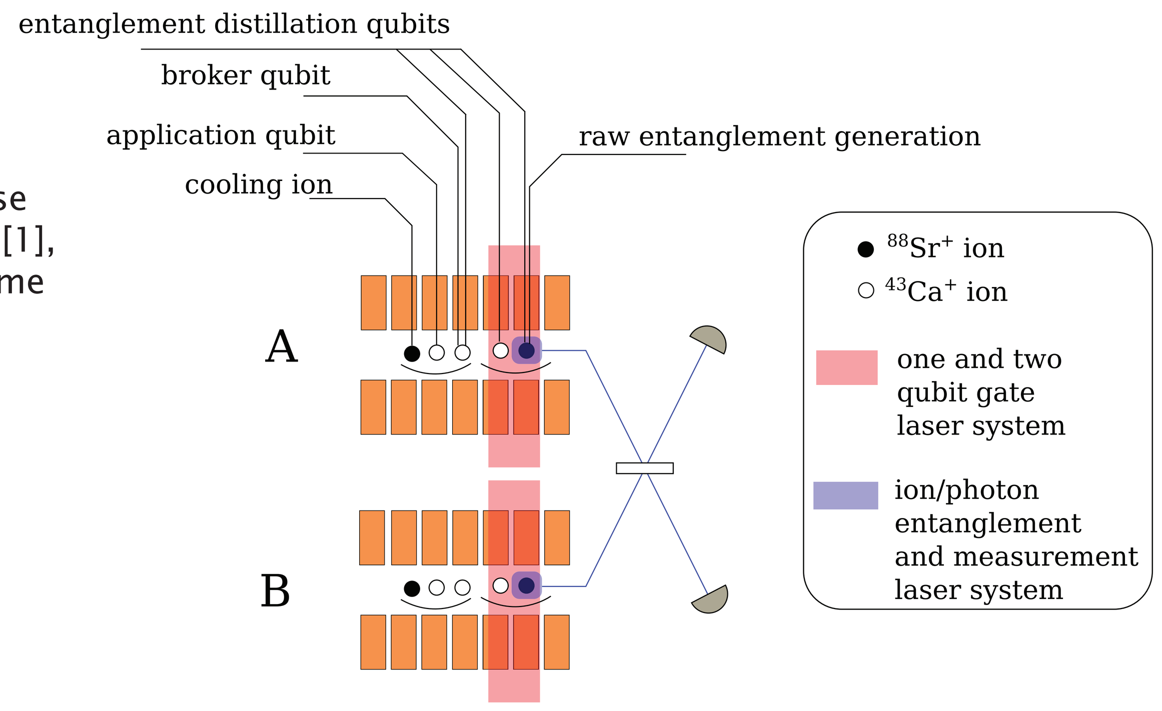


The goal

To generate high fidelity entanglement over a quantum network, ions in separate traps emit single photons whose interference is measured to create a raw entangled state [1], which is purified using an entanglement distillation scheme [2].

High fidelity local operations improve the fidelity by over two orders of magnitude, using two ion species, without focussed beam addressing, with only nearest neighbour operations and two trap zones.

[1] Moehring et al., Nature 2007
[2] Nigmatullin et al., New J. Phys. 2016

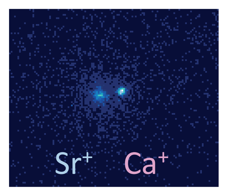


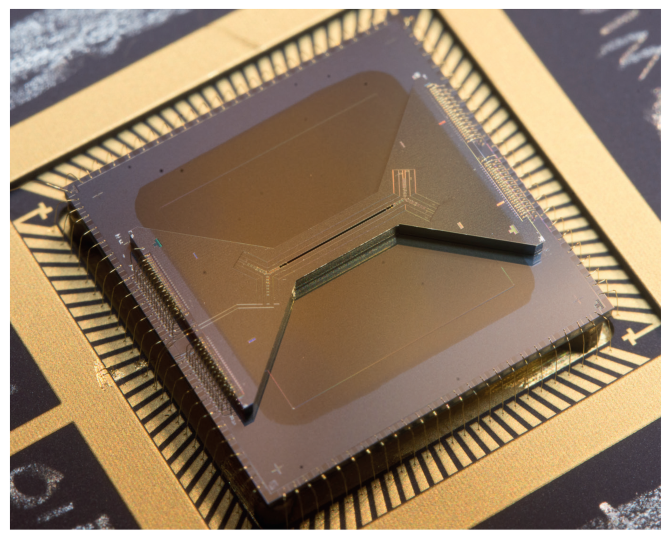
The requirements

- Prepare Ca⁺ & Sr⁺ crystals ✓
- Prepare quantum states and measure ✓ [99.83%]
- Single qubit gates ✓ [99.9934(3)%]
- Local Ca-Ca gates ✓ [99.9(1)%]

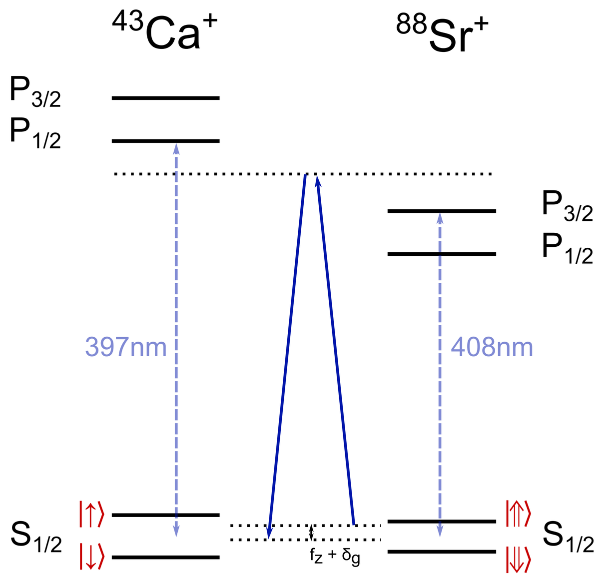
- Local Ca-Sr gates ✓ [~85%, WIP]
- Create ion-photon entanglement ✓ [~77%, WIP]

- Trap in a pair of multi-zone traps
- Create remote ion-ion entanglement





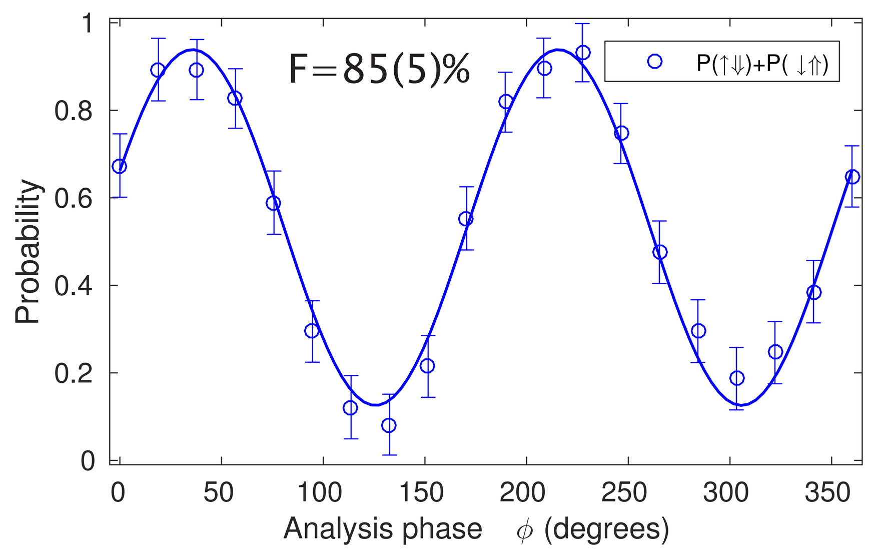
Mixed species gate



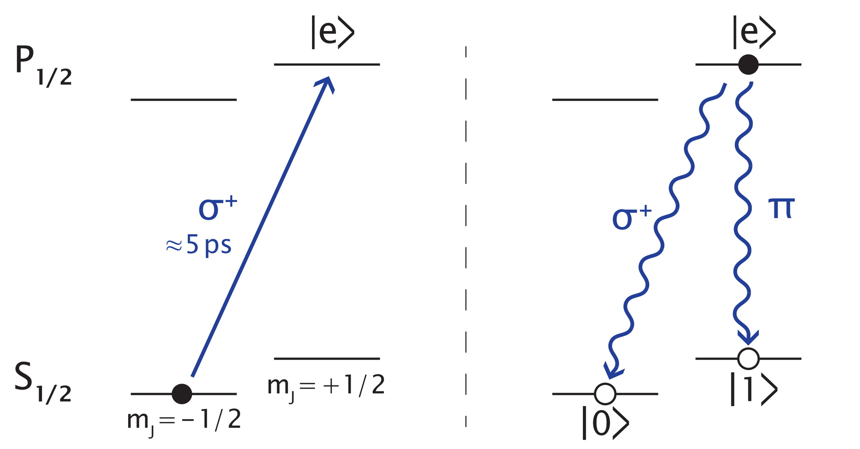
A single pair of Raman beams, detuned by approximately 10 THz from the S-P transitions of both $^{88}Sr^+$ and $^{43}Ca^+$, provide the force for a gemoetric phase gate [3].

The gate mechanism does not depend on the qubit splitting, hence is robust to qubit frequency noise and allows gates between different ion species ($^{40}Ca^+$, $^{43}Ca^+$, $^{88}Sr^+$).

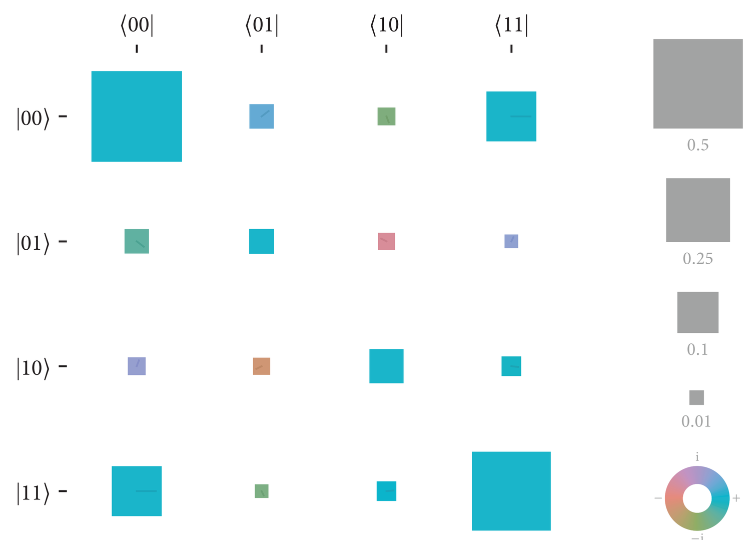
[3] Ballance et al., Nature 2015



Ion-photon entanglement



A $^{88}Sr^+$ ion is excited to one of its short-lived $P_{1/2}$-states using a picosecond laser. The photon emitted in the decay is entangled in frequency and polarisation with the resulting Zeeman qubit.

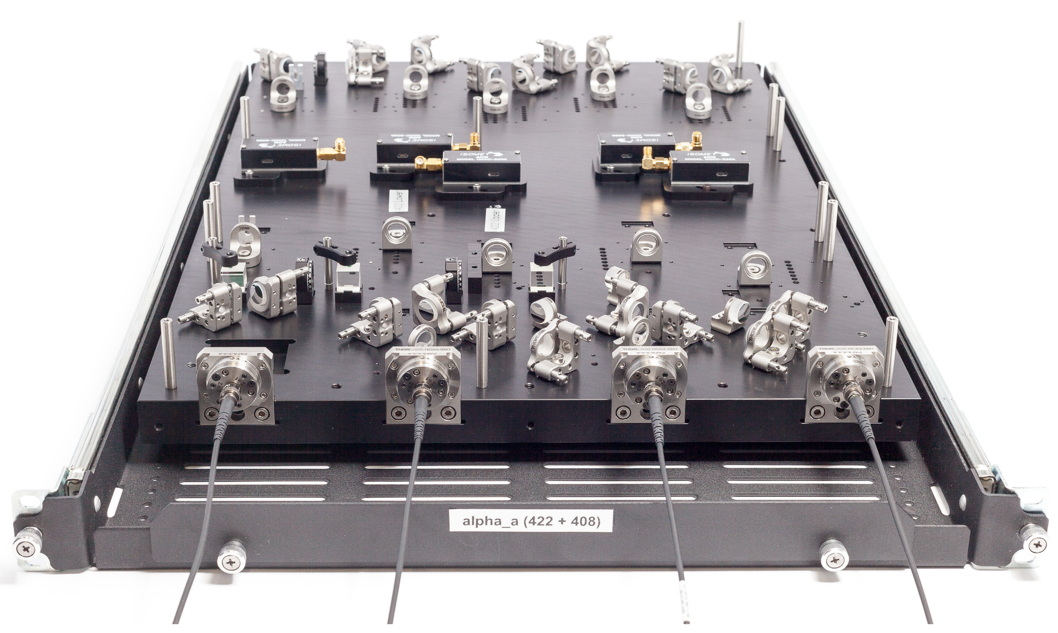


In our initial demonstration, with the emission collected perpendicular to the magnetic field, we obtained a Bell state fidelity of 0.77 (entanglement of formation 0.081).

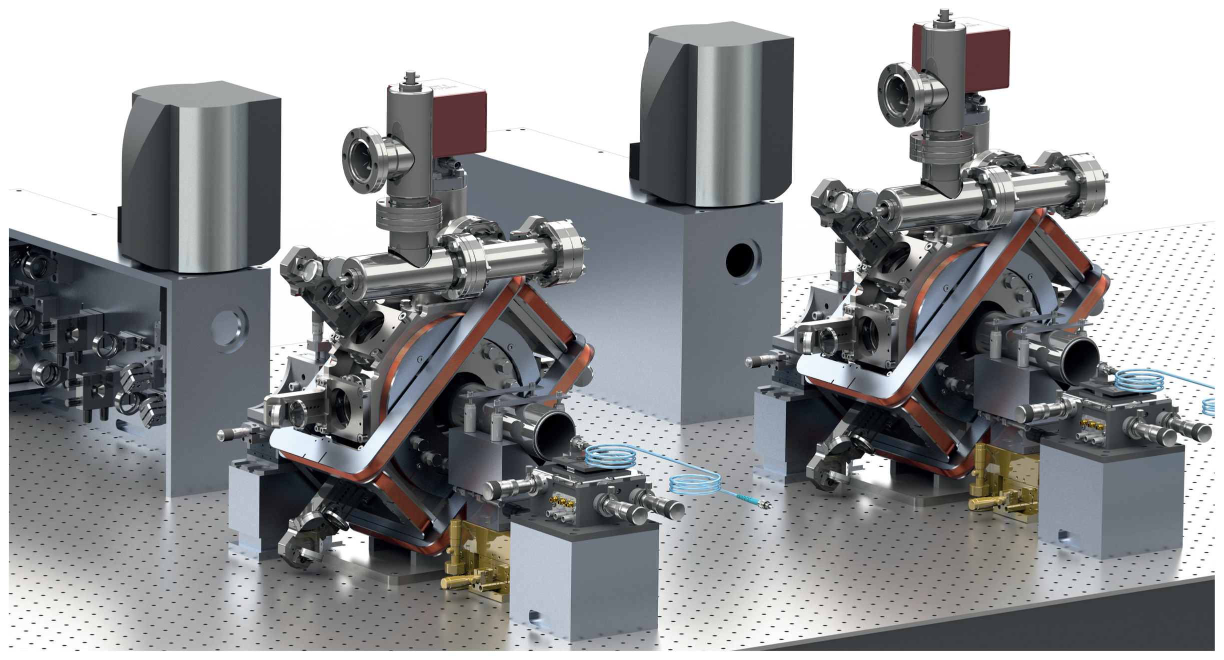
Rack-mounted laser systems

Compact rack-mounted laser systems for $^{43}Ca^+$ and $^{88}Sr^+$ have been built to house the lasers, optics, AOMs and EOMs necessary for each beam path, with independent control for each of the two trap systems.

1/2" optics are built on to breadboards which stack in a rack, along with the drivers, controllers and diagnostics to run the system, reducing the footprint of more than an optics table into two racks.



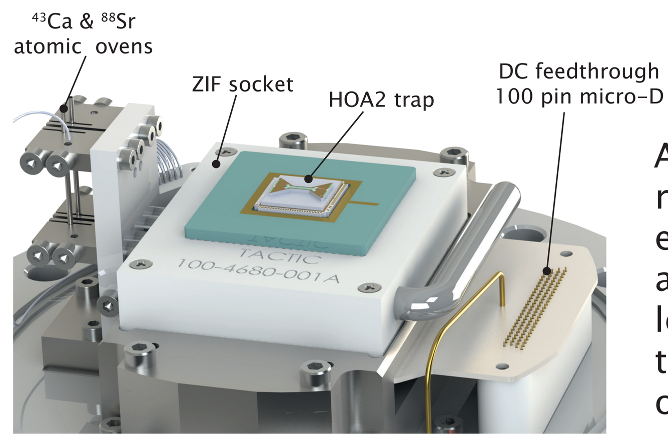
Twin ion trap systems



Two identical vacuum system assemblies, each containing a HOA2 linear multi-zone surface trap (courtesy of Sandia Nat'l Labs), are currently under construction.

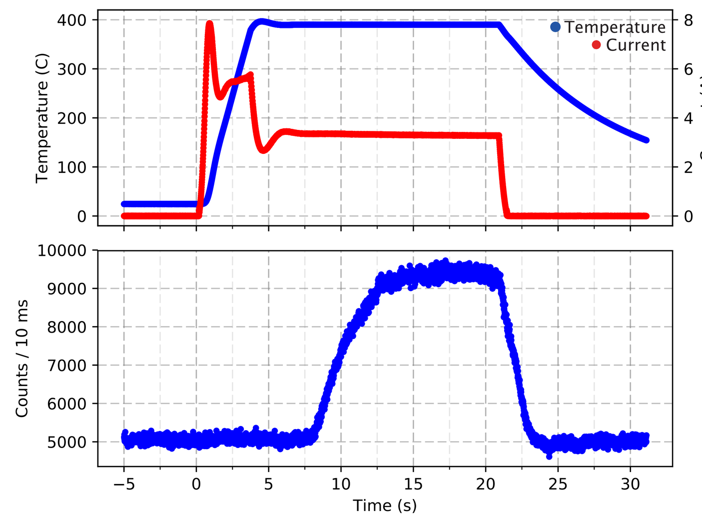
Each have two imaging systems, with independent readout for $^{43}Ca^+$ and $^{88}Sr^+$ on the back, and a high N.A. (0.6) lens to fibre couple ion emission on the front.

Closed loop oven control



As the time between recrystallisation events may limit experiments, we have designed atomic ovens optimised for short loading times, by reducing their thermal mass and controlling the oven temperature.

A PID control loop of the temperature is closed using a thermocouple spot-welded to the oven. The system reaches operating temperature in ~5 seconds, with atomic flux reaching steady state in ~12 seconds.



www.physics.ox.ac.uk/users/iontrap/
keshav.thirumalai@physics.ox.ac.uk
Department of Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom

IOTA
NQIT Networked Quantum Information Technologies
UK National Quantum Technologies Programme
EPSRC Pioneering research and skills
dstl