L J Stephenson, D P Nadlinger, B C Nichol, P Drmota, K Thirumalai, A C Hughes, V M Schäfer, S An, J F Goodwin, A M Steane, D M Lucas, C J Ballance

UNIVERSITY OF OXFORD

A two-node trapped-ion quantum network

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

A promising approach to scaling ion-trap quantum computers to arbitrarily large numbers of qubits is to use many similar ion trap processors (nodes) connected together in a modular network. Raw entanglement between ions in separate nodes, created by interfering and measuring 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 the nodes, allows us to harness the advantages of both species for their respective tasks.

Here we present work showing entanglement between two $^{88}Sr^+$ ions trapped in separate vacuum systems, a prerequisite of which is measuring entanglement between a single ion and the photon emitted after excitation by a picosecond laser.

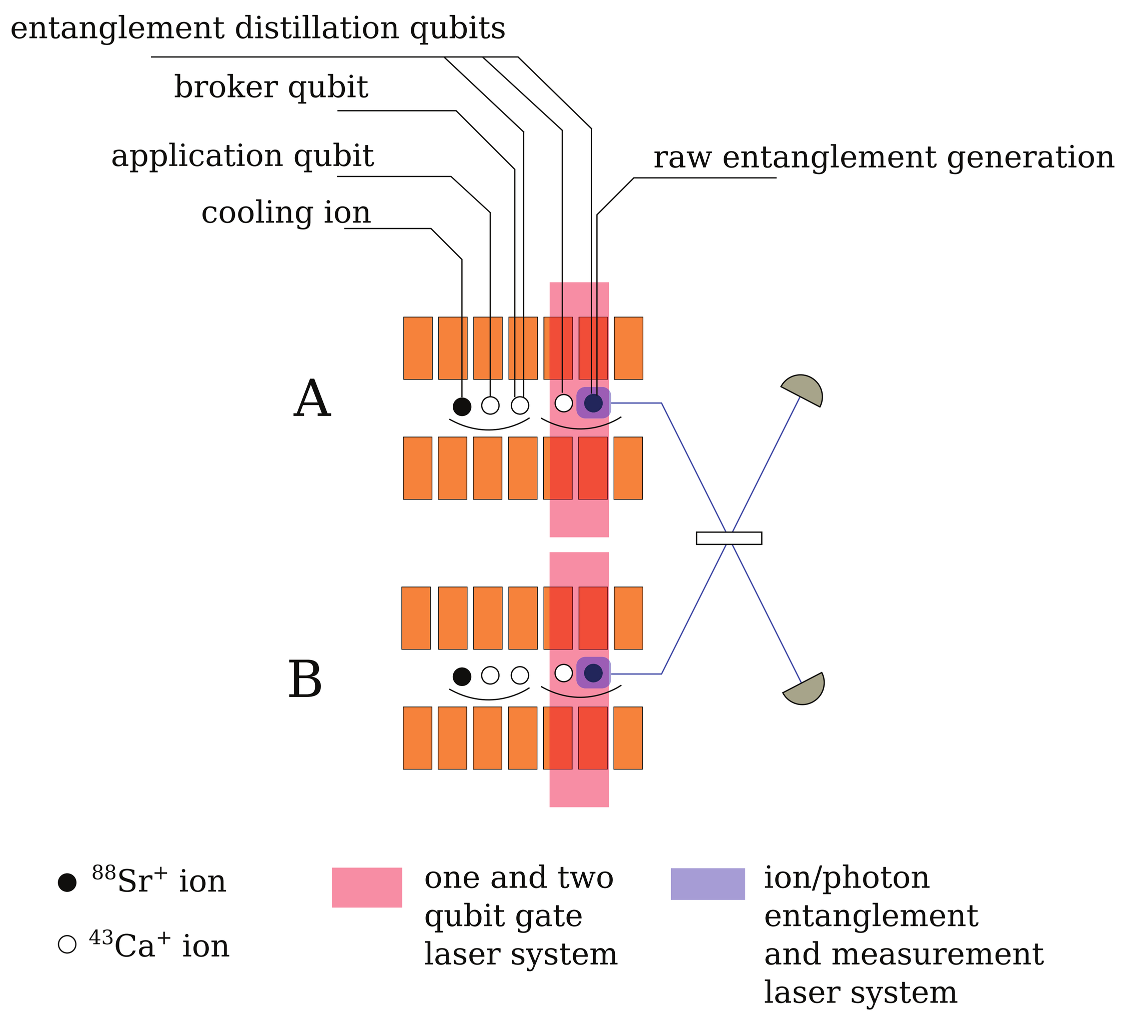
In addition, as part of the next stage to purify the entanglement generated using local operations, we also present work done on mixed species gates preformed between $^{88}Sr^+$ and $^{43}Ca^+$.

The goal

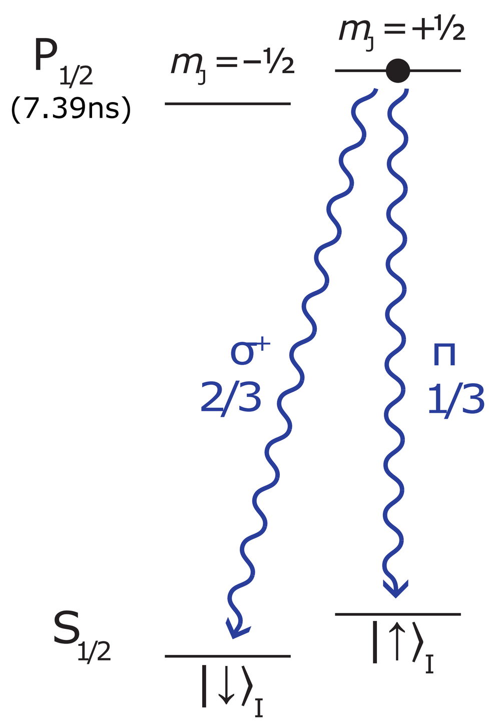
We aim to generate high fidelity entanglement distributed over a quantum network. To generate raw entangled states, ions in separate traps emit single photons whose interference is measured [1]. This entanglement can then be purified using an entanglement distillation scheme [2].

This optimised distillation scheme improves the remote entanglement fidelity using only nearest neighbour operations in two trap zones, requiring two ion species in each trap but not requiring focussed beam addressing.

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



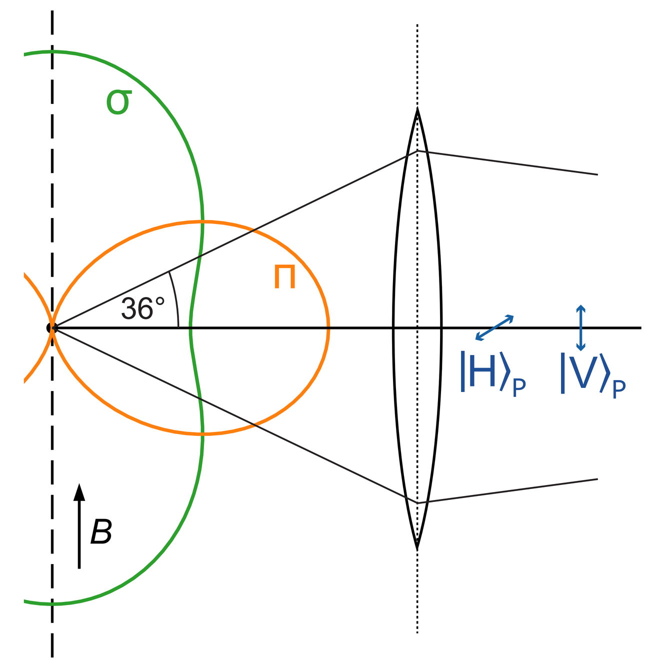
Ion-photon entanglement



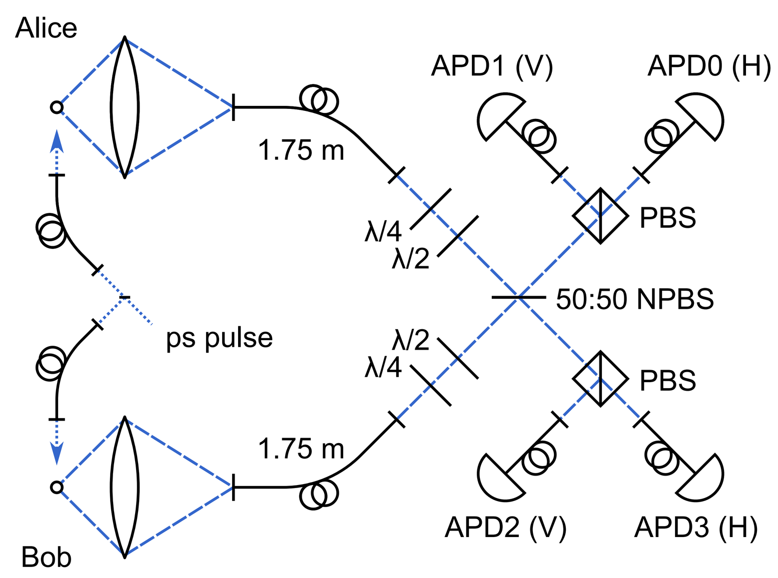
We need to generate photons entangled with our ion qubits in order to implement our ion-photon network. We do this by exciting a $^{88}Sr^+$ ion to one of its short-lived $P_{1/2}$-states using a picosecond laser. The emitted 422 nm photon is entangled in frequency and polarisation with the resulting Zeeman qubit.

We collect photons perpendicular to the magnetic field — coupling into a single (Gaussian) fibre mode avoids polarisation mixing. The fibre adds an uncontrolled unitary rotation to the photon state, but this varies only slowly and so can be corrected by using waveplates to apply the inverse rotation.

We measure ion-photon Bell state fidelities of 97.90(12)% and 97.70(12)% for the two traps.

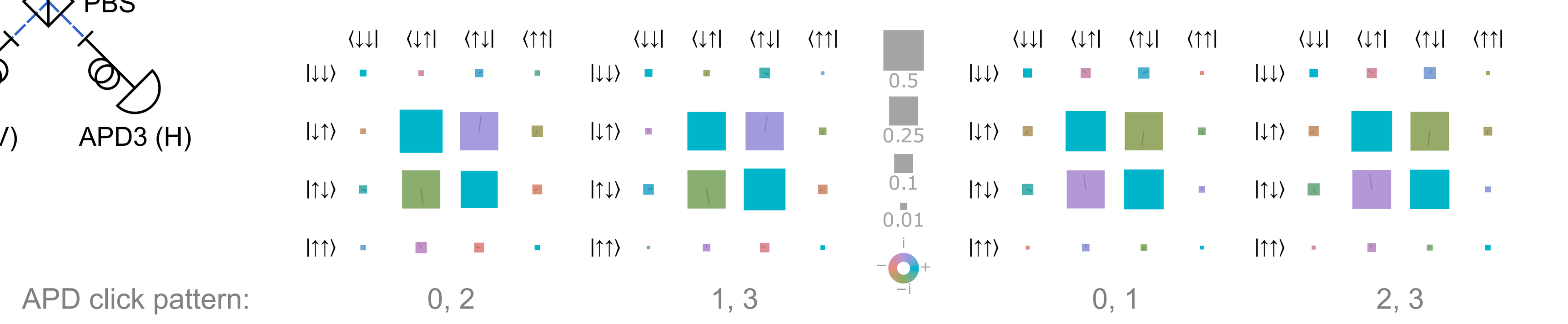


Remote entanglement between traps

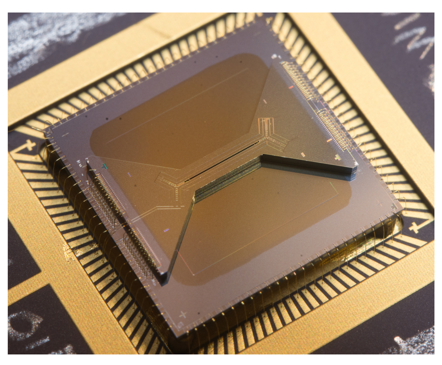


To create ion-ion entanglement, we intefere the photons emitted simultaneously from each ion on a 50:50 beamsplitter. The two-photon state is measured using a four detector scheme, probabilistically heralding the projection of the ion-ion state into a Ψ^+ or Ψ^- Bell state, dependent on the detector click pattern.

Our two-ion state has an average fidelity of 94.0(5)% with the maximally entangled state, and is created at a rate of 182 Hz.



The ion traps



We have constructed two identical vacuum systems, each containing a HOA2 linear multi-zone surface trap (courtesy of Sandia National Labs), designed to operate with both $^{43}Ca^+$ and $^{88}Sr^+$ and allow high-fidelity mixed species gates.

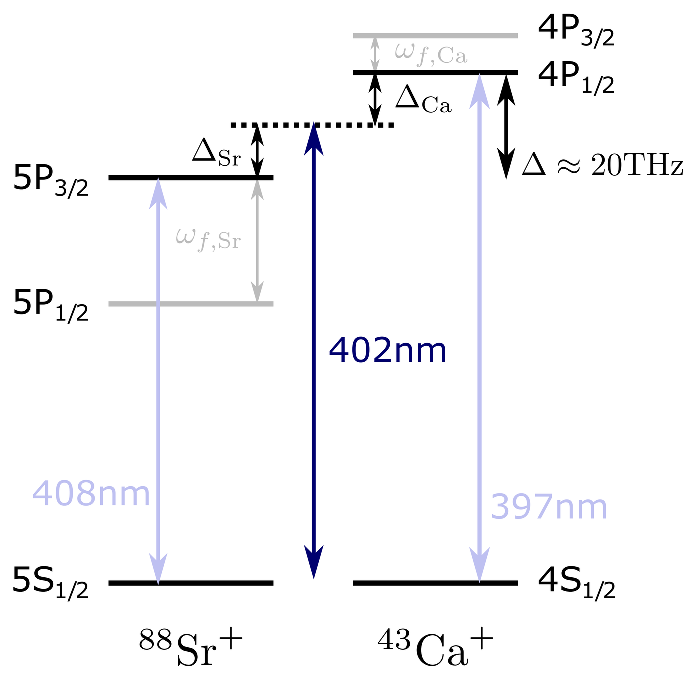
Each has two imaging systems: one through a slot in the trap to allow independent readout of $^{43}Ca^+$ and $^{88}Sr^+$, and the other with numerical aperture 0.6 to couple ion emission directly into an optical fibre.

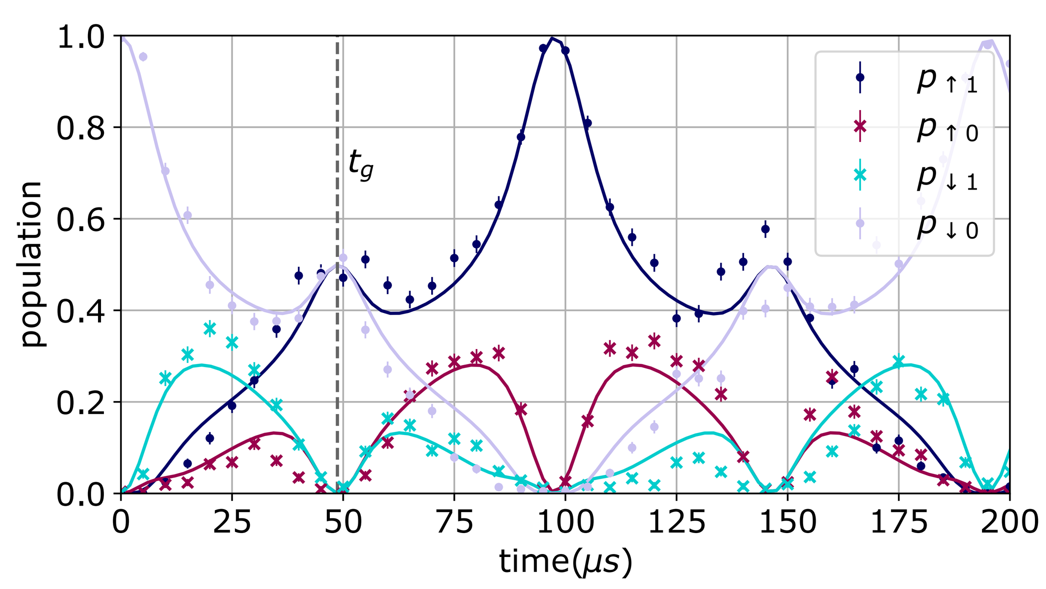
Closed-loop temperature controlled atomic ovens allow us to load ions in ~10 s from cold.

$^{43}Ca^+$- $^{88}Sr^+$ entangling gates

In order to perform entanglement distillation we must swap the entanglement between the two traps from the $^{88}Sr^+$ ions to two $^{43}Ca^+$ ions, requiring high fidelity mixed species gates.

We have demonstrated a geometric phase gate between $^{43}Ca^+$ and $^{88}Sr^+$ in another Paul trap experiment. A single pair of Raman lasers is used to perform a gate on the magnetically sensitive ground state qubit of both species simultaneously. After normalising for errors in state preparation and measurement the preliminary best gate fidelity is F=99.5(3)%.



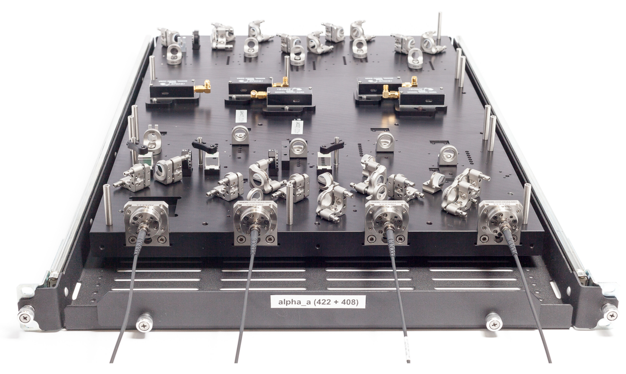


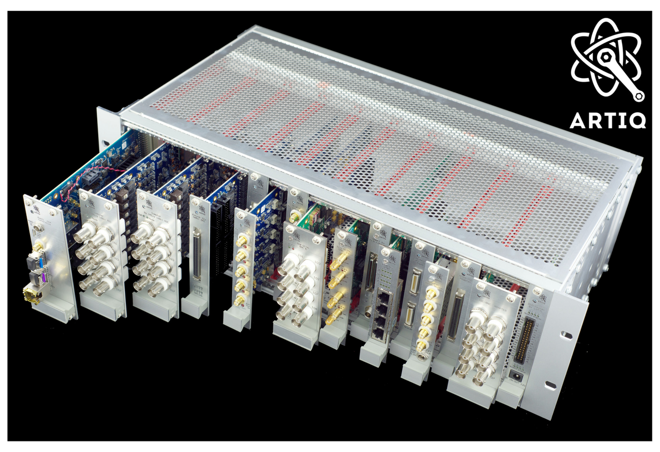
Infrastructure and control system

Using conventional techniques, the laser sources and modulators to operate two mixed species traps would occupy a prohibitive amount of optics table space, and be consuming to construct and maintain. To minimise the footprint, increase the stability and improve the repeatability of these systems, we have built compact rack-mounted laser systems.

1/2” optics are mounted onto custom baseplates 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 standard 19" racks.

The ARTIQ system is used for real-time experimental control. Multiple crates of Sinara open-source hardware are deployed throughout the lab, synchronised via optical fibre links. ARTIQ also features a Python-based language for simple and fast development of complex experiment sequences.





UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME
EPSRC Pioneering research and skills
[dstl]

laurent.stephenson@physics.ox.ac.uk
www.physics.ox.ac.uk/users/iontrap/
Department of Physics, Clarendon Laboratory, Parks Rd, Oxford, OX1 3PU, United Kingdom