Improving the Capabilities of a Quantum Network

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Trapped atomic ions present an ideal platform for quantum computing due to their long coherence times, precise control, and inherent qubit connectivity. These systems have already demonstrated the functionality of small, fully controllable universal quantum computers. However, scaling remains a significant challenge. As the number of qubits increases, control becomes more difficult due to factors like single-qubit addressing and spectral crowding. Solving this challenge is critical, as most practical applications require a larger number of qubits to achieve "quantum advantage" — where quantum computers outperform classical ones in specific tasks. This scaling challenge is not unique to ion-based systems but affects all quantum computing platforms.

One potential solution is to interconnect discrete, fully controllable quantum processor modules via photonic entanglement networks, rather than concentrating all qubits in a single processor. In this approach, single photons emitted by ions create quantum connections between different processors allowing for flexible, long-distance connections with minimal decoherence. Additionally, photons can be routed to connect any two processors in a network, not just adjacent ones, allowing for highly adaptable quantum networks.

Our team at the University of Oxford has developed a pioneering ion trap network, comprising two separate ion trap processors. The system has successfully demonstrated proof-of-principle protocols for distributed quantum computing [1], blind quantum computing [2], quantum communications [3], and remote quantum sensing [4]. While a two-node network is sufficient for these initial experiments, it is far from enough to prove the scalability required for practical quantum computing. Therefore, we aim to advance the network's capabilities by developing the techniques and technologies that will allow for distributing entanglement across multiple nodes; i.e. to demonstrate a quantum repeater as shown in Fig. 1.

There are 3 key milestones to be reached before performing this experiment. An improved BSA is being built to increase the rate and fidelity of remote entanglement. A high-quality, high-NA collection lens will then be designed and fabricated to optimally match the mode of the collected photons to that of the fibre being coupled into. This should also increase the rate of remote

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entanglement. This should allow us to beat our already world record winning results demonstrated in [1-4]. A multi-fibre array system is being developed to act as a switch and allow selective routing of photons from the trapped ions. This would show proof-of-principle for adaptable networking between multiple quantum processors.

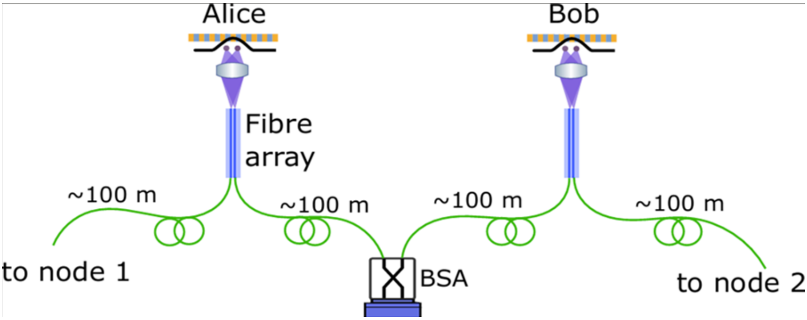

FIG. 1. Ion-ion entanglement is created between Alice and Bob through photonic entanglement swapping at the Bell state analyser (BSA). Additional ion-photon Bell pairs are created between Alice and Node1, and Bob and Node2. Local operations map the Alice-Bob entanglement onto the Alice-Node1 and Bob-Node2 entanglement, creating end-to-end entanglement between photons at Node1 and Node2.

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[2] P. Drmota *et al.*, *PRL* **132** 150604 (2023).
[3] D. P. Nadlinger *et al.*, *Nature* **607** 682 (2022).
[4] B. C. Nichol *et al.*, *Nature* **609** 689 (2022).