# WORKSHOP ON QUANTUM ERROR CORRECTION WITH NEUTRAL ATOMS

Wednesday 2nd July 2025.

Venue: Technology and Innovation Centre, 99 George Street, Glasgow, G1 1RD

Map: https://www.strath.ac.uk/maps/?building=technologyinnovationcentre

Workshop Webpage: https://qca-cluster.org/workshop-on-error-correction-with-neutral-atoms/

## Workshop Programme 10:00-16:15

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| 09:30 | 10:00 | Arrival and Registration | | |
| **10:00** | **11:00** | **Session 1: An Introduction to Quantum Error Correction** | | |
| 10:00 | 10:10 | Jonathan Pritchard | University of Strathclyde | *Welcome* |
| 10:10 | 11:00 | Joschka Roffe | University of Edinburgh | *An Introduction to Quantum Error Correction* |
| 11:00 | 11:30 | Coffee | | |
| **11:30** | **12:30** | **Session 2: Experimental Tweezer Array Platforms** | | |
| 11:30 | 12:00 | Nicholas Spong | NQCC | *Toward the Megaquop: Progress and challenges of the neutral atom platform* |
| 12:00 | 12:15 | Kieran Craig | University of Strathclyde | *Cryogenic Dual Species Arrays for QEC* |
| 12:15 | 12:30 | Simon Cornish | Durham University | *A three-species tweezer array* |
| 12:30 | 13:30 | Lunch | | |
| **13:30** | **16:00** | **Session 3: Quantum Error Correction in Practise** | | |
| 13:30 | 14:00 | Madelyn Cain | Harvard University | *Fault-tolerant computation and decoding with neutral atoms* |
| 14:00 | 14:15 | Stefano Veroni | University of Oxford | *Universal Fault-Tolerant Quantum Computation without Measurements* |
| 14:15 | 14:30 | Stergios Koutsioumpas | University Of Edinburgh | *Leveraging symmetries for efficient and fast quantum error correction.* |
| 14:30 | 14:45 | Oliver Brown | University of Edinburgh | *Low-latency Software Stacks* |
| 14:45 | 15:00 | Linnea Grans-Samuelsson | University of Oxford | *A partition function framework for estimating logical error curves in stabilizer codes* |
| 15:00 | 15:30 | Coffee | | |
| 15:30 | 15:45 | Steph Foulds | University of Strathclyde | *Discrete Quantum Walks with Near-Term Neutral Atom Hardware Error Modelling* |
| 15:45 | 16:00 | Chris Corlett | University of Bristol | *Speeding Up Quantum Measurement Using Space-Time Trade-Off* |
| **16:00** | **16:15** | **Session 4: Discussion to identify opportunities for collaboration** | | |

# WORKSHOP ON QUANTUM ERROR CORRECTION WITH NEUTRAL ATOMS

Abstract Booklet

## Session 1: An Introduction to Quantum Error Correction

### *An Introduction to Quantum Error Correction*

Joschka Roffe, University of Edinburgh

Quantum error correction protocols will play a central role in the realisation of quantum computing; the choice of error correction code will influence the full quantum computing stack, from the layout of qubits at the physical level to gate compilation strategies at the software level. In this talk, I will introduce the theory and implementation of quantum error correction codes. Starting from the very basics, I will describe how quantum error correction codes can be represented via the stabiliser framework, how logic can be compiled via techniques such as lattice surgery and magic state injection, and how this will impact both the size and cost of full-scale quantum computing systems. Following this, I will introduce quantum low-density parity-check codes, a resource-efficient alternative to the surface code that is particularly well-suited to neutral atom architectures.

## Session 2: Experimental Tweezer Array Platforms

### *Toward the Megaquop: Progress and challenges of the neutral atom platform*

Nicholas Spong, NQCC

With the introduction of the MQUOP, focus is shifting from early NISQ-era demonstrations toward error-corrected devices. In the past year, Google have successfully implemented a surface and repetition codes on their latest Willow superconducting chips, achieving error rates of up to $\sim 10^{-10}$ (and uncovering some new challenges in the process!). The neutral atom platform might be expected to take a similar trajectory. A team including Harvard and QuEra have demonstrated magic state distillation, syndrome extraction and error correction through feed-forward.

These, and complementary advances across other platforms, raise the possibility of entering the MQUOP regime through error correction in the coming decade. However, with superconducting devices racing to improve yield & calibration, ionic systems battling to shuttle across junctions & realise remote entanglement, and traditional neutral atom platforms suffering from slower readout and rearrangement times, realising the MQUOP vision in any platform will require improvements to both hardware and software, across the classical and quantum stack.

This talk will give an overview of the current state of the art for the neutral atoms, highlighting challenges for realising MQUOP within the platform. This will include an update on work ongoing at NQCC to support quantum computing with neutral atoms in the UK.

### *Cryogenic Dual Species Arrays for QEC*

Kieran Craig, University of Strathclyde

Neutral atoms arrays have become a prominent platform for quantum computation due to the scalability of optical tweezers allowing for up to 1000 identical qubits, in which multi-qubit gates are mediated by interactions between highly excited Rydberg states. To realise fault tolerance on a neutral atom platform it is necessary to be able to perform independent and cross-talk free mid-circuit readout of ancilla qubits.

One approach to overcome this limitation is to use dual-species arrays, which naturally provides a separation in read-out wavelengths to suppress cross-talk, whilst allowing engineering of different inter and intra-species couplings. We present progress towards realising a cryogenic platform for neutral atom quantum computing based on Rydberg operations using two atomic species. Co-located arrays of rubidium and caesium are created via independent SLM-generated red-detuned dipole trap at 810nm (Rb) and 935nm (Cs) with 5 μm Rb-Cs spacing, while the cryogenic environment should provide ultra-low background pressure for long trap lifetimes via cryopumping.

*A three-species tweezer array*

Simon Cornish, Durham University

We will briefly describe the capabilities of the three-species tweezer array experiment in Durham where we trap and manipulate arrays of Rb and Cs atoms and RbCs molecules. We will highlight some of the recent advances using molecules including high-fidelity entanglement, multistate readout and mid-sequence detection of formation errors, as well as our on-going work at interfacing Rydberg atoms and molecules. As an outlook, we will describe near term upgrades to the apparatus that include two-species Rydberg excitation and scaling to larger 2D arrays.

**Session 3: Quantum Error Correction in Practise**

*Fault-tolerant computation and decoding with neutral atoms*

Madelyn Cain, Harvard University

Quantum error correction (QEC) is required for large-scale computation, but incurs a significant resource overhead. By jointly decoding logical qubits in algorithms composed of transversal gates, this overhead can be reduced by a factor of the code distance, but at the cost of increased decoding complexity. In this talk, I will present strategies for fast and accurate correlated decoding. By directly decoding relevant logical operator products as they propagate through the circuit, we simplify the task to closely resemble that of a single-qubit memory propagating through time, reducing the problem size and enabling fast matching-based algorithms to be applied in surface code computation. We then utilize these tools in experiments with reconfigurable arrays of neutral atoms, demonstrating reduced logic gate overhead and performance of 2.14(13)x below-threshold in a four-round characterization circuit on individual surface codes by leveraging atom loss detection and machine learning. These results establish foundations for practical correlated decoding with neutral atoms, and provide a pathway to directly extend single-qubit QEC techniques to transversal algorithms.

*Universal Fault-Tolerant Quantum Computation without Measurements*

Stefano Veroni, Oxford University

A major challenge in performing quantum error correction is implementing fast reliable measurements and feed-forward. In neutral-atom platforms, alternative measurement-free schemes are possible, relying on unconditional qubit resets, a continuous supply of qubits, and non-local connectivity.

We show that also universal quantum computation can be made fault-tolerant without mid-circuit measurements. To this end, we introduce a measurement-free deformation protocol of the Bacon-Shor code to realize a logical CCZ gate, enabling a universal set of fault-tolerant operations. Separately, we demonstrate that it can be efficiently concatenated without measurements nor a universal logical gate set, by means of the "disposable Toffoli gadget". For a Bacon-Shor quantum-memory, we then observe a measurement-free concatenation threshold slightly greater than $10^{-3}$, and even higher pseudo-thresholds.

Finally, the measurement-free QEC cycle rate is compared to state-of-the-art feed-forward in neutral-atoms, showing potential speed-ups.

*Leveraging symmetries for efficient and fast quantum error correction*

Stergios Koutsioumpas, University of Edinburgh

Quantum Error Correction is a necessary component of future Quantum Computing experiments, however it requires high overheads in the finite and near term regime. Two of the most difficult problems in QEC are efficient decoding, ie the classical feedback system to reduce the accumulation of errors and efficient logical gates. I will present our recent work that tackles those problems by leveraging the inherent symmetries of error correcting codes. Specifically, I will introduce AutDEC: an automorphism ensemble decoder that achieves linear runtime complexity for Quantum LDPC codes and AutQEC: a package to find efficient logical gate implementations for platforms where transversal logic is allowed such as Neutral Atoms systems. Finally, I will present some follow ups on logical circuit synthesis and experimental results.

*Low-latency Software Stacks*

Oliver Brown, University of Edinburgh

Quantum error correction will require complex, heterogeneous classical compute to diagnose and respond to errors within the narrow window afforded by qubit lifetimes. In this short talk we examine the concept of latency in classical compute, and some of the software techniques that help us minimise latency in HPC.

*A partition function framework for estimating logical error curves in stabilizer codes*

Linnea Grans-Samuelsson, University of Oxford

The optimal thresholds of quantum error-correcting stabilizer codes have early on been related to phase transitions within disordered statistical mechanics models of Random Bond Ising-type. In this talk, I present a framework for obtaining the full logical error curves for two families of decoding strategies: maximum partition function decoders and probabilistic partition function decoders. Maximum likelihood (optimal) decoding is a member of the former family, while maximum probability (MP) decoding is a member of the latter. The logical error rates for the two families are given by two ratios of partition functions, and estimating the error rates through these ratios is expected to be generally more sample-efficient than estimating the error rates by counting the number of failures of the corresponding decoders. At zero temperature, the difference between the two ratios measures to what degree MP decoding can be improved by accounting for degeneracy among maximum probability errors, through methods such as ensembling.

*Discrete Quantum Walks with Near-Term Neutral Atom Hardware Error Modelling*

Steph Foulds, University of Strathclyde

Quantum walks, the quantum analogue to the classical random walk, have been shown to be able to model fluid dynamics. Using error modelling for multiqubit Rydberg gates via two-photon adiabatic rapid passage (ARP) on single species neutral atom arrays, we present the gate sequences and final state fidelities for some toy quantum walks, including 'lazy' quantum walks. In particular, we highlight the benefits of native multi-control gates when implementing quantum walks with nearest neighbour connectivity. Ongoing work aims to improve these final state fidelities with dual species arrays and error correction.

*Speeding Up Quantum Measurement Using Space-Time Trade-Off*

Chris Corlett, University of Bristol

We present a scheme for speeding up quantum measurement. The scheme builds on previous protocols that entangle the system to be measured with ancillary systems. In the idealized situation of perfect entangling operations and no decoherence, it gives an exact space-time trade-off meaning the readout speed increases linearly with the number of ancilla. We verify this scheme is robust against experimental imperfections through numerical modeling of gate noise and readout errors, and under certain circumstances our scheme can even lead to better than linear improvement in the speed of measurement with the number of systems measured. This hardware-agnostic approach is broadly applicable to a range of quantum technology platforms and offers a route to accelerate midcircuit measurement as required for effective quantum error correction.