Circuit-Based Leakage-to-Erasure Conversion in a Neutral-Atom Quantum Processor

Matthew N. H. Chow,[1,2,3,*,‡] Vikas Buchemmavari,[2,3,†,‡] Sivaprasad Omanakuttan,[2,3]
Bethany J. Little,[1] Saurabh Pandey,[1] Ivan H. Deutsch,[2,3] and Yuan-Yu Jau[1,2,3]

[1] *Sandia National Laboratories, Albuquerque, New Mexico 87123, USA*

[2] *Center for Quantum Information and Control (CQuIC),*

In the absence of such hardware-specific techniques, circuit-based methods, such as leakage-detection units (LDUs) and leakage-reduction units (LRUs), may be used to detect or reduce (without detecting) leakage errors [25,26]. LDUs map the bit of information specifying whether a data atom is within the qubit subspace or not onto the 0-1 states of an ancilla qubit and do so without disturbing the information in the data qubit in the case of no leakage. These circuit-based approaches to leakage errors have been previously demonstrated in other hardware such as trapped ions and superconducting qubits [27–31]. While thresholds for common codes (e.g., the toric code) drop to zero is the presence of uncorrected leakage, finite thresholds exist when LDUs or LRUs are inserted [20,21,32].

In this work, we study the application of LDUs for neutral atoms and perform proof-of-principle demonstrations of their experimental implementation, whereby we successfully detect leakage while preserving the coherence of the data qubit. The objectives of an LDU are twofold: (1) detect whether or not some data atom is present and in the computational subspace, and (2) do so in a way that preserves the information in that data atom. In this work, our qubit states are the "clock-state" Zeeman sublevels in the hyperfine ground-state manifold of cesium atoms in optical tweezers. For hyperfine ground-state qubits in alkali atoms, there are three major pathways for the atom to leak out of the computational space (see Fig. 1). The first is atom loss from the trap due to background gas collisions, heating after many gates or movement operations, and failure of recapture after the traps are turned o during entangling operations. The second is Rydberg leakage, where the population is unintentionally left behind in a Rydberg state after entangling operations, either due to coherent over-rotations or blackbody-induced transitions to nearby Rydberg states. The third leakage mechanism is so-called hyperfine leakage into nonqubit Zeeman sublevels of the hyperfine ground manifold due to decay from excited states. Our objective is to demonstrate the detection of leakage via these three pathways with a circuit that preserves the coherence of the data atom.

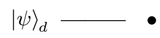
In Sec. II, we describe the major leakage pathways in detail and show how they can be accounted for and detected using LDUs. This is achieved by turning Rydberg leakage into atom loss via the repulsive force of the trap for population left behind in a Rydberg state (Rydberg antitrapping) and by using two-qubit gates that are sensitive to the choice of Zeeman sublevel. We perform a proof-of-principle demonstration of the standard LDU, showing that the state of an ancilla atom correctly labels the presence or absence of a data atom within the qubit subspace without disturbing the information in the data atom. Then, in Sec. III, we discuss how this LDU can be modified for neutral-atom platforms to provide "free refilling" of atoms by performing a SWAP. We further implement a teleportation-based version of the SWAP LDU, which has only one entangling gate and free refilling capability.

These demonstrations are made possible by a three-outcome measurement protocol (explained below in Sec. I A), which retains the atom in the trap after detection and can projectively detect atom loss by direct measurement, allowing us to benchmark the performance of the LDUs [33–35]. We also explore the benefits that three-outcome measurements confer upon LDUs. In the absence of the three-outcome measurement capability, the circuits presented here may still be used to mitigate leakage errors,

(a)

although in some cases they work only as LRUs, which reduce, but do not detect, leakage errors.

(a)



the $F = 3$ ($F =$

is expected to be far outweighed by the advantages of free refilling and cooling by replacement (for details, see Appendix A 5).

A. Teleportation-based SWAP LDU

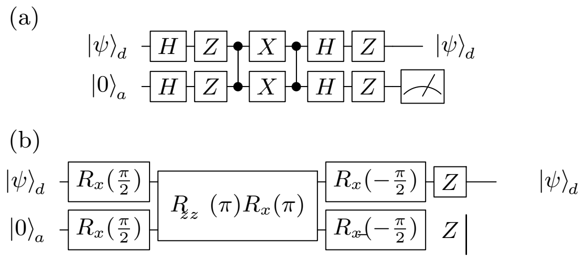
In the SWAP LDU, we can combine the second entangling gate and the following measurement into a measurement-feedback gate instead, as in a one-bit teleportation circuit [71,72]. This circuit has previously been used as an LRU that reinitializes a qubit in the computacontext of embedding SWAP LRUs into a surface code and that appropriate scheduling of LRUs has been shown to still produce a fault-tolerant implementation.

To check the coherence of the quantum information after the teleportation-based LDU, we teleport a $|+y\rangle$ and a $|-x\rangle$ state and perform a phase scan of an effectively local final $R_\phi(\pi/2)$ pulse to reveal the phase of the resulting superposition state on the ancilla atom (see Fig. 4). As the physical local rotations can only perform $R_z(\theta)$, we split the global $R_\phi(\pi/2)$ into two $R_\phi(\pi/4)$ pulses and apply a local $R_z(\pi)$ on the original data qubit in between to effectively cancel its participation in the R_ϕ gate [74,75]. Compared to the direct data-atom measurement in the case of no LDU, the contrast of the resulting teleported state is reduced from 96(1)% to 90(2)% for the $|-x\rangle$ state and from 98(1)% to 92(2)% for the $|+y\rangle$ state.

IV. SUMMARY AND OUTLOOK

The experiments in this work have demonstrated proof-

$R_{zz}\ (\frac{\pi}{4})$


(a)
$|\psi\rangle_d$
$|0\rangle_a$
H
Z
X
H
Z
$|\psi\rangle_d$
(b)
$|\psi\rangle_d$
$|0\rangle_a$
$R_x(\frac{\pi}{2})$
$R_{zz}(\pi)R_x(\pi)$
$R_x(-\frac{\pi}{2})$
Z
$|\psi\rangle_d$

[13] A. G. Radnaev *et al.*, A universal neutral-atom quantum computer with individual optical addressing and non-destructive readout, arXiv:2408.08288 [quant-ph].
[14] D. Bluvstein *et al.*, Logical quantum processor based on reconfigurable atom arrays, Nature **626**, 58 (2024).
[15] I. Cong, H. Levine, A. Keesling, D. Bluvstein, S.-T. Wang, and M. D. Lukin, Hardware-e cient, fault-tolerant quantum computation with Rydberg atoms, Phys. Rev. X **12**, 021049 (2022).
[16] Y. Wu, S. Kolkowitz, S. Puri, and J. D. Thompson, Erasure conversion for fault-tolerant quantum computing in alkaline earth Rydberg atom arrays, Nat. Commun. **13**, 4657 (2022).
[17] S. Omanakuttan, V. Buchemmavari, J. A. Gross, I. H. Deutsch, and M. Marvian, Fault-tolerant quantum compu-

of dephasing mechanisms in a standing-wave dipole trap, Phys. Rev. A **72**, 023406 (2005).
[48] Sometimes LLSD is referred to as nondestructive readout (NDRO) in the literature. We use LLSD to avoid confusion over the term “nondestructive,” which could accidentally imply nonprojective measurements. LLSD is a projective measurement of both the atom state and the atom presence in the trap.
[49] Alternative compilations of LDUs may instead choose to perform the opposite logic and flip the interpretation of the readout result on the ancilla. We consistently use identity for no leakage and bit flip on the ancilla for convenience.
[50] The uncertainty reported here is where the likelihood drops by a factor of 2 relative to the maximum (i.e., half width at half maximum) in a one-dimensional cut along the contrast parameter, holding the other fitting parameters fixed at the optimum.
[51] H. Levine, A. Keesling, G. Semeghini, A. Omran, T. T. Wang, S. Ebadi, H. Bernien, M. Greiner, V. Vuletić, H. Pichler, and M. D. Lukin, Parallel implementation of high-fidelity multiqubit gates with neutral atoms, Phys. Rev. Lett. **123**, 170503 (2019).
[52] S. Jandura and G. Pupillo, Time-optimal two- and three-qubit gates for Rydberg atoms, Quantum **6**, 712 (2022).
[53] A. Pagano, S. Weber, D. Jaschke, T. Pfau, F. Meinert,

impurity atoms immersed in an ultracold gas, Phys. Rev. Lett. **109**, 235301 (2012).

[78] A. J. Daley, P. O. Fedichev, and P. Zoller, Single-atom cooling by superfluid immersion: A nondestructive method for qubits, Phys. Rev. A **69**, 022306 (2004).

[79] A. Griessner, D. Jaksch, and P. Zoller, Cavity-assisted nondestructive laser cooling of atomic qubits, J. Phys. B: At., Mol. Opt. Phys. **37**, 1419 (2004).

[80] R. Belyansky, J. T. Young, P. Bienias, Z. Eldredge, A. M. Kaufman, P. Zoller, and A. V. Gorshkov, Nondestructive cooling of an atomic quantum register via state-insensitive Rydberg interactions, Phys. Rev. Lett. **123**, 213603 (2019).

[81] A. Cao, W. J. Eckner, T. Lukin Yelin, A. W. Young, S. Jandura, L. Yan, K. Kim, G. Pupillo, J. Ye, N. Darkwah Oppong, and A. M. Kaufman, Multi-qubit gates and Schrödinger cat states in an optical clock, Nature **634**, 315 (2024).

[82] M. Peper, Y. Li, D. Y. Knapp, M. Bileska, S. Ma, G. Liu, P. Peng, B. Zhang, S. P. Horvath, A. P. Burgers, and J. D. Thompson, Spectroscopy and modeling of ^{171}Yb Rydberg states for high-fidelity two-qubit gates, arXiv:2406.01482 [physics.atom-ph].

[83] http://energy.gov/downloads/doe-public-access-plan

[84] S. Meiboom and D. Gill, Modified spin-echo method for measuring nuclear relaxation times, Rev. Sci. Instrum. **29**, 688 (1958), https://pubs.aip.org/aip/rsi/article-pdf/29/8/688/19287064/688_1_online.pdf.