Experimental repetitive quantum error correction

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Motivation

Repeated quantum error correction is a necessity for a large-scale quantum computer.

A popular error-correction protocol is the quantum repetition code [1]. It encodes a qubit in a multipartite entangled state and utilizes majority voting for error detection and correction.

We implement up to three subsequent correction steps of the 3 qubit phase-flip repetition code.

Measurement-free QEC

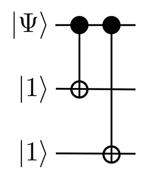
Measurements disturb the motional state thus complicating repeated error correction.

Measurement-free QEC has realistic demands on the quality and speed of the preparation/measurement.

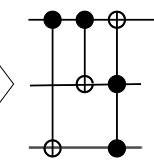
The fault tolerant threshold does not decrease significantly [2].

The quantum repetition code

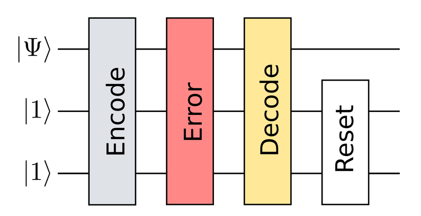
Encoding:

$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \Rightarrow$  $\Rightarrow \alpha|000\rangle + \beta|111\rangle$

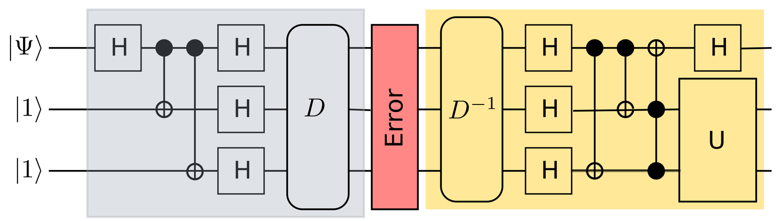
Decoding and correction:

single-qubit error $\Rightarrow$ $\alpha|001\rangle + \beta|110\rangle$, $\alpha|010\rangle + \beta|101\rangle$, $\alpha|100\rangle + \beta|011\rangle$ $\Rightarrow$  $\Rightarrow \alpha|0\rangle + \beta|1\rangle$

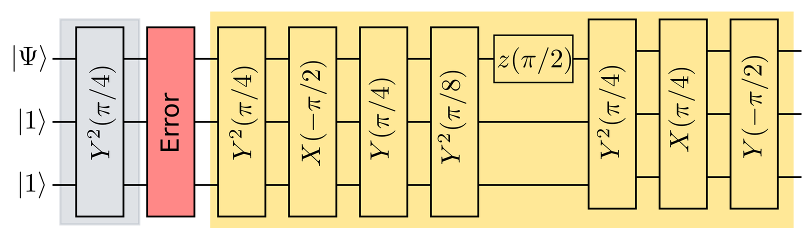
Creating the pulse sequence



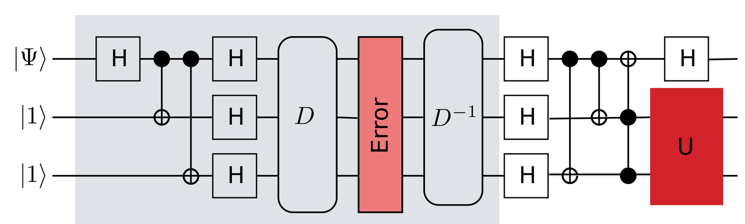
Adapted quantum repetition code



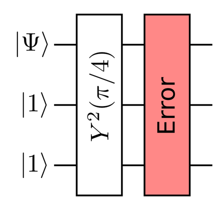
Optimization procedure



Our algorithm



Neglect the state of the ancilla qubits after the correction stage.



A single entangling gate implements the encoding stage.

Optimizing the algorithm

Modified gradient ascent pulse engineering (GRAPE) algorithm [3]

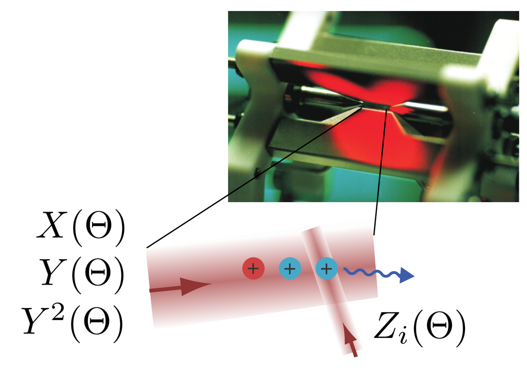
Pulse sequence: $U = \prod_m e^{-i\,\Theta_m\,H_m}$

Performance function Φ that has maximum for exact algorithm.

Optimize pulse length with gradient: $\Theta_m = \Theta_m + \frac{\partial \Phi}{\partial \Theta_m}$

Add random pulses H_m from time to time.

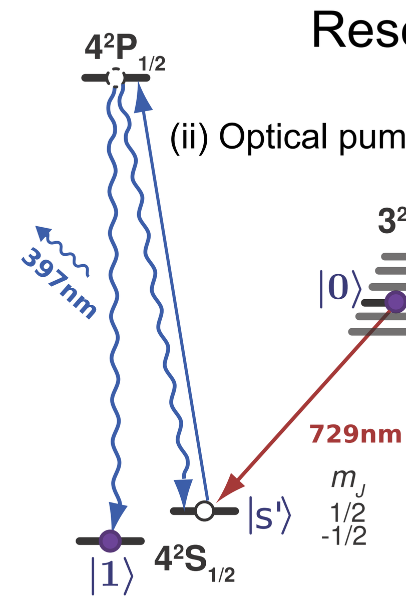
Experimental System



No interferometric stability between paths needed.

$X(\Theta)\,Y(\Theta)$	collective local operations	F=99%
$Z_i(\Theta)$	single qubit z rotations	F=99%
$Y^2(\Theta)$	Mølmer Sørensen type entangling operations	F=98%

Resetting the qubit



(ii) Optical pumping from $|s'\rangle$ to $|1\rangle$

(i) Shelve population of ancilla ions from $|0\rangle$ to $|s'\rangle$

Heating 0.014 phonons/reset

Experimental results

97% χ_0

identity process

Step1

χ_1

QEC ⇒ With errors: F=90%
Without errors: F=90%

Step2

χ_2

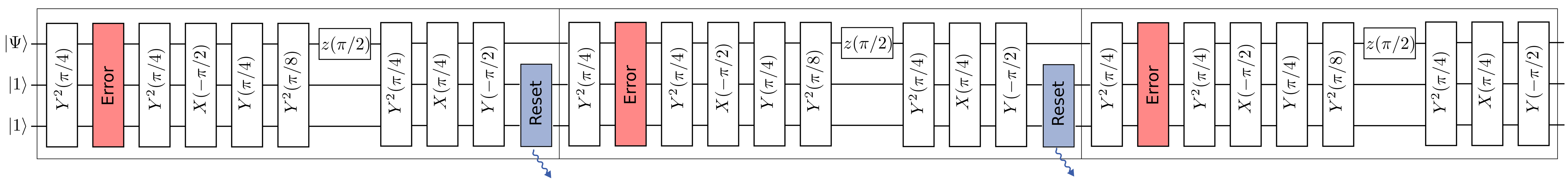
QEC ⇒ With errors: F=80%
Without errors: F=80%

Step3

χ_3

QEC ⇒ With errors: F=70%
Without errors: F=72%

With errors: Data taken from average over all possible single qubit errors.

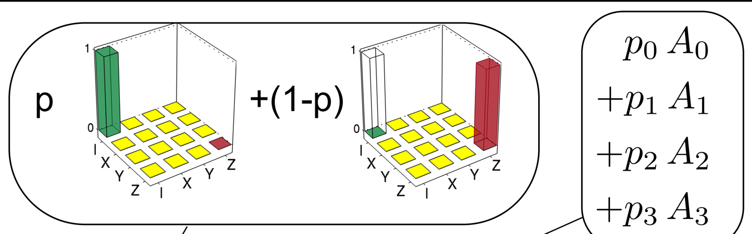


Simulating an environment

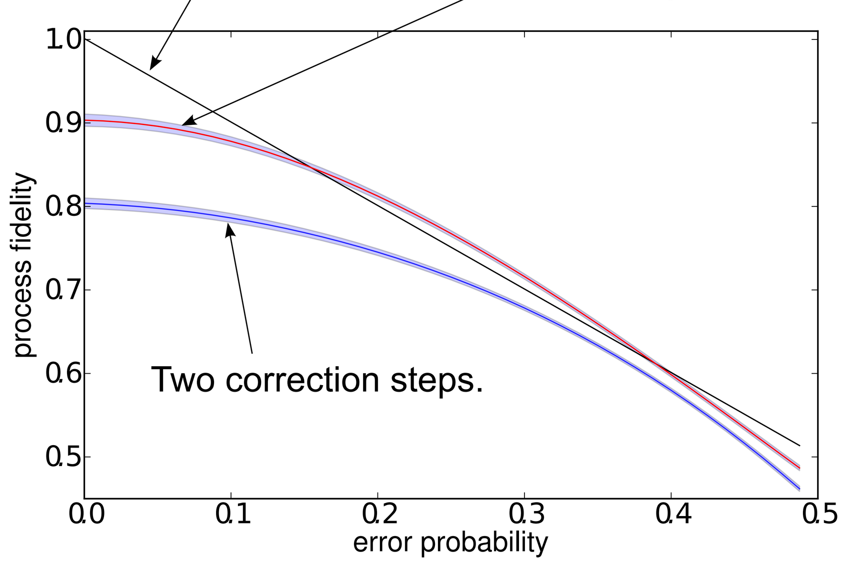
The algorithm corrects for single phase-flips but in a realistic environment, also two and three-qubit phase-flips occur.

An error model can be described by defining the error probabilities p_n that an n-qubit phase-flip occurs.

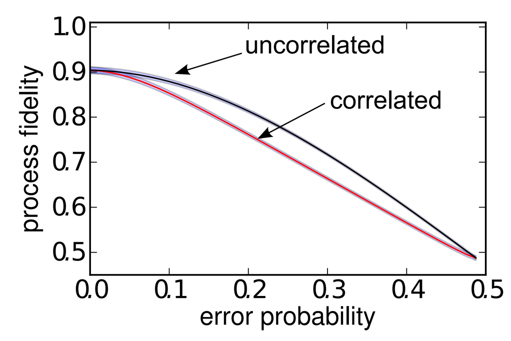
If the p_n are known depending on of the single-qubit error probability p the behavior of the algorithm can be reconstructed.



A_n... Measurement vector for a single-qubit process tomography.



Repetition code and noise correlation.



Outlook

Our optimization procedure allows us to implement complicated algorithms.

Useful error correction will need a protocol that protects also for correlated noise.

Use the dissipative toolbox to perform dissipative driven quantum computation.

References

[1] Nielsen, Chuang, Quantum Computation and Quantum Information

[2] G. A. Paz-Silva et al. Phys. Rev. Lett. **105**, 100501 (2010).

[3] V. Nebendahl et. al. Phys. Rev. A **79**, 012312 (2009).