Small quantum algorithms realized in a scalable ion trap array

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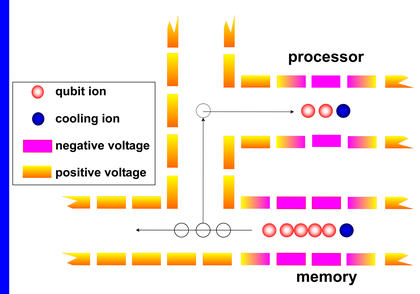
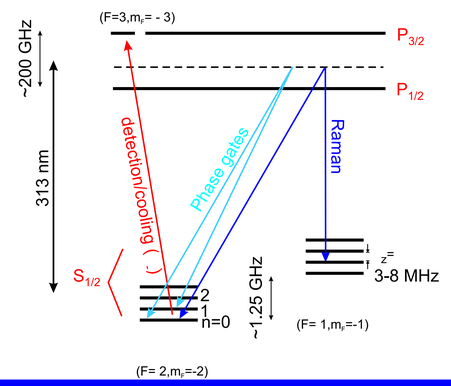
Supported by: ARDA-NSA, NIST

General approach

Multiplexed architecture

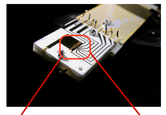


Laser configuration for $^9Be^+$



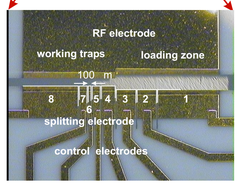
6 Zone alumina wafer trap

Trap chip



Two layers of alumina, lower layer electrodes are mirror image around the trap axis. Low pass filters for control electrodes integrated on the chip structure.

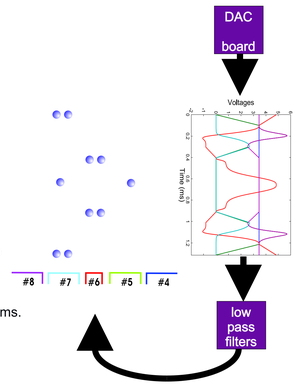
Trapping region



Control voltages for Separation

Control voltage waveforms are created by first simulating the trap potentials with SIMION. Then electrode voltages as a function of time are calculated to achieve the desired variation of the axial potential.

In the example to the right, the potential minimum is first moved from electrode #7 to electrode #6.Then the well is relaxed so that the Coulomb repulsion drives the two ions towards electrodes #5 and #7. Then electrode #6 drives a potential wedge between the ions placing them in separate potential wells over #5 and #7. All steps are reversed in the second half of the waveforms.



State of the Art at NIST

Operation	Timescale	Error probability
Initialize qubit(s)	5 s	10^{-4}
Single qubit gate	1 s	10^{-4}
Two qubit gate	10 s	3 %
Measure	200 s	10^{-3}
Movement	distance· 30 ns/ m	no failure detected
Separation/ Recombination	400 s	no failure detected
Recooling	200 s	shows up in two qubit gate
Memory decoherence	> 14 s	negligible

Recent publications

D. Leibfried, M. D. Barrett, T. Schaetz, J. Britton, J. Chiaverini, W. M. Itano, J. D. Jost, C. Langer, and D. J. Wineland, *Towards Heisenberg-Limited Spectroscopy with Multiparticle Entangled States,* Science 304, 1476 (2004).

M. D. Barrett, J. Chiaverini, T. Schaetz, J. Britton, W. M. Itano, J. D. Jost, E. Knill, C. Langer, D. Leibfried, R. Ozeri, and D. J. Wineland, *Deterministic quantum teleportation of atomic qubits,* Nature 429, 737 (2004).

T. Schaetz, M. D. Barrett, D. Leibfried, J. Chiaverini, J. Britton, W. M. Itano, J. D. Jost, C. Langer, and D. J. Wineland, *Quantum Dense Coding with Atomic Qubits,* Phys. Rev. Lett. 93, 040505 (2004).

J. Chiaverini, D. Leibfried, T. Schaetz, M. D. Barrett,R. B. Blakestad, J. Britton, W.M. Itano, J. D. Jost, E. Knill, C. Langer,R. Ozeri, and D. J. Wineland *Realization of quantum error correction,* Nature 432, 603 (2004).

T. Schaetz, M. D. Barrett, D. Leibfried, J. Britton, J. Chiaverini, W. M. Itano, J. D. Jost, E. Knill, C. Langer, and D. J. Wineland, *Enhanced Quantum State Detection Efficiency through Quantum Information Processing.* Phys. Rev. Lett. 94, 010501 (2005).

J. Chiaverini, R. B. Blakestad, J. Britton, J. D. Jost, C. Langer, D. Leibfried, R. Ozeri, D. J. Wineland *Surface-Electrode Architecture for Ion-Trap Quantum Information Processing,* quant-ph/0501147 (2005)

R. Ozeri, C. Langer, J. D. Jost, B. L. DeMarco, A. Ben-Kish, B. R. Blakestad, J. Britton, J. Chiaverini, W. M. Itano, D. Hume, D. Leibfried, T. Rosenband, P. Schmidt, D. J. Wineland *Hyperfine Coherence in the Presence of Spontaneous Photon Scattering,* quant-ph/0502063 (2005)

C. Langer, R. Ozeri, J. D. Jost, J. Chiaverini, B. DeMarco, A. Ben-Kish, R. B. Blakestad, J. Britton, D. B. Hume, W. M. Itano, D. Leibfried, R. Reichle, T. Rosenband, T. Schaetz, P. O. Schmidt, D. J. Wineland *Long-lived qubit memory using atomic ions,* quant-ph/0504076 (2005)

J. Chiaverini, J. Britton, D. Leibfried, E. Knill, M. D. Barrett, R.B. Blakestad, W. M. Itano, J. D. Jost, C. Langer, R. Ozeri, T. Schaetz, and D. J. Wineland, *Implementation of the Semiclassical Quantum Fourier Transform in a Scalable System,* Science 308, 997 (2005)

D. Leibfried, E. Knill, S. Seidelin, J. Britton, R.B. Blakestad, J. Chiaverini, D. B. Hume, W. M. Itano, J. D. Jost, C. Langer, R. Ozeri, R. Reichle, and D. J. Wineland, *Creation of a six-atom 'Schrödinger cat' state,* Nature 438, 639 (2005)

GHZ-states of up to 6 ions

GHZ-state generation and entanglement detection

GHZ states for 3,4 and 5 ions of the form

$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\ldots\uparrow\rangle + |\downarrow\downarrow\ldots\downarrow\rangle)$$

are produced by sandwiching an appropriate phase gate in between /2-pulses. Upon free precession these states pick up phase N-times faster than a single ion (top trace). This makes such states useful for spectroscopy beyond the standard limit.

To prove genuine N-particle entanglement, one can use the witness operator

$$\hat{W}(N) = \hat{I}/2 - |\mathrm{GHZ}\rangle\langle\mathrm{GHZ}|$$

When the contrast of the phase sweep is larger than 0.5 the expectation value of the witness is negative by the inequality

$$\mathrm{Tr}(\hat{\rho}(N)\hat{W}(N)) = 1/2 - F$$
$$= 1/2 - 1/2(P_{N\uparrow} + P_{N\downarrow}) - \rho_{N\uparrow N\downarrow}$$
$$\leq 1/2 - 2\rho_{N\uparrow N\downarrow} = 1/2 - \mathrm{contrast}$$

The contrast of the phase sweeps is a lower bound for fidelity since the gate that produces the GHZ state is used a second time to "decode" the phase information. This implies that the fidelity of our GHZ states could be as high as the square-root of the contrast.

Experimental Results

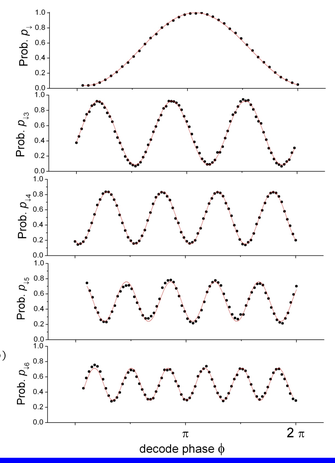
$\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$
contrast: 97%
fidelity: 99%

$\frac{1}{\sqrt{2}}(|\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle)$
contrast: 84%
fidelity: 89%
W < -0.68

$\frac{1}{\sqrt{2}}(|\uparrow\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\downarrow\rangle)$
contrast: 69.8(3)%
fidelity: 76(1)%
W < -0.51(2)

$\frac{1}{\sqrt{2}}(|\uparrow\uparrow\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\downarrow\downarrow\rangle)$
contrast: 52.7(3)%
fidelity: 60(2)%
W < -0.20(4)

$\frac{1}{\sqrt{2}}(|\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\rangle)$
contrast: 41.9(4)%
fidelity: 50.9(4)
W < -0.018(8)



Three Qubit Bitflip-Error Correction

The Code

Our implementation is based on a 3-qubit stabilizer code specially developed for easy implementation with a single phase gate. The code has no classical analog and is therefore not locally equivalent to the repetition code or a CSS code.

The code is based on the generators {ZZX,ZXZ} and can either detect or correct within several different correction protocols. In our experiment we corrected for bit-flip (X) errors on all three qubits.

Check matrices for some protocols

Error detection
(X-errors on qubit 1, all errors on 2,3)

	III	XII	IXI	IIX	IZI	IIZ
ZZX	0	1	1	0	0	1
ZXZ	0	1	0	1	1	0

Error correction
(X-errors on all qubits)

	III	XII	IXI	IIX
ZZX	0	1	1	0
ZXZ	0	1	0	1

Error correction
(X-errors on qubit 1, Z-errors on 2,3)

	III	XII	IZI	IIZ
ZZX	0	1	0	1
ZXZ	0	1	1	0

Error correction
(X-errors on qubit 1 and 2, Z-errors on 2)

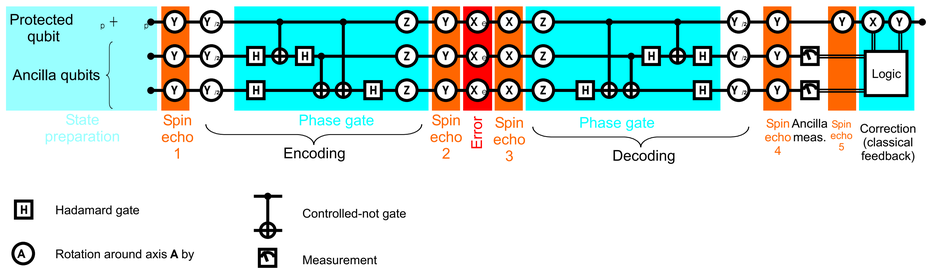
	III	XII	IZI	IXI
ZZX	0	1	0	1
ZXZ	0	1	1	0

etc.

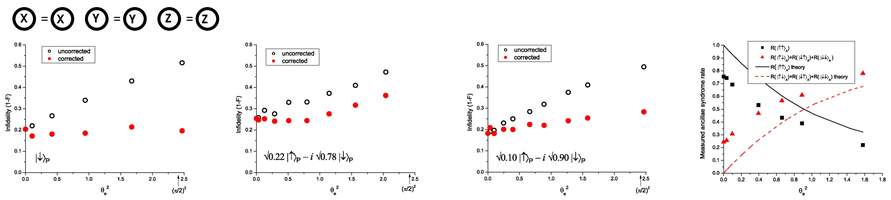
Experimental Results

We encoded states of the form | + | and then applied an "error", a controlled pulse with rotation angle e. This rotation was applied either to the encoded state (red symbols) or unencoded state (black symbols). For small angles the infidelity should scale as $_e^2$, therefore the black curve is roughly linear. For the encoded state the linear error is suppressed by the error correction, therefore it starts out quadratically in $_e^2$.

Experimental Implementation

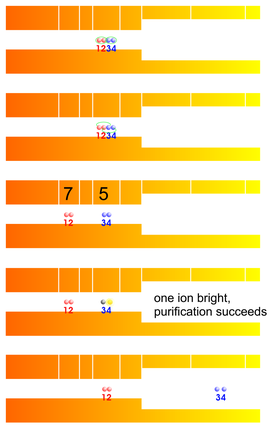


Hadamard gate
Controlled-not gate
Rotation around axis **A** by
Measurement



Entanglement Purification (Distillation)

Experimental implementation



i) Partially entangle ion pairs 1;2 and 3;4 with phase-gate on egyptian mode.

ii) Entangle across the pairs with phase gate on the COM, ion 1 with 3 and ion 2 with 4 to create correlations for purification.

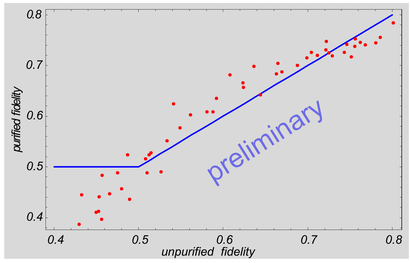
iii) Move qubits 1;2 0.6 mm to trap 7.

iv) Measure qubits 3;4, if they are found to be in | or | assume 1;2 are purified. Otherwise assume purification failed.

v) Move qubits 1;2 to trap 5. Do state tomography to 1;2 to find fidelity.

vi) Repeat whole sequence except step ii) and subsequent postselection to find reference fidelity of the unpurified pair 1;2.

Results



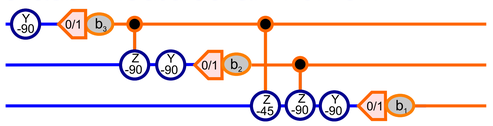
We can purify entanglement in the fidelity range 52% to 75%.

The data is consistent with distillation from 52% to 75% fidelity by iteration of the process. Iteration would need recooling of the ions which we have not demonstrated yet.

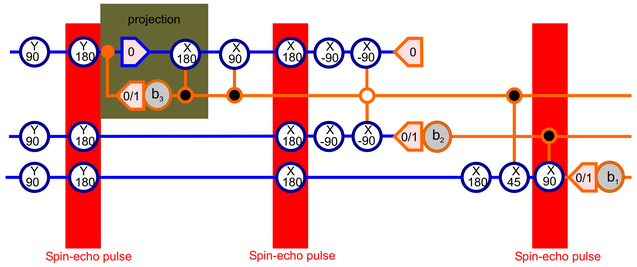
- 4 two qubit phase gates
- Separation of entanglement (300 m)
- Manipulation of entanglement after separation
- Coherent manipulation conditioned on measurement

Three Qubit Quantum Fourier Transform

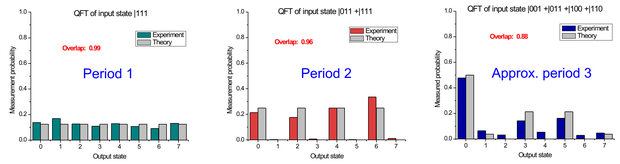
3-Qubit Measured QFT network



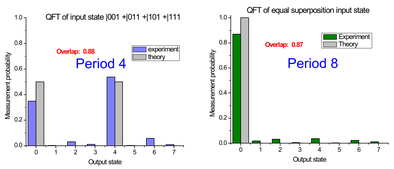
Experimental implementation



Results



Overlap:

$$\left(\sqrt{\mathrm{data}}\cdot\sqrt{\mathrm{theory}}\right)^2$$

J. Chiaverini et al., submitted