An open-system quantum simulator with trapped ions

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AG Quantenoptik und Spektroskopie

Goal: Demonstrate experimentally a toolbox of operations for simulating open-system quantum dynamics.

How? Combine universal set of coherent operations with engineered decoherence.

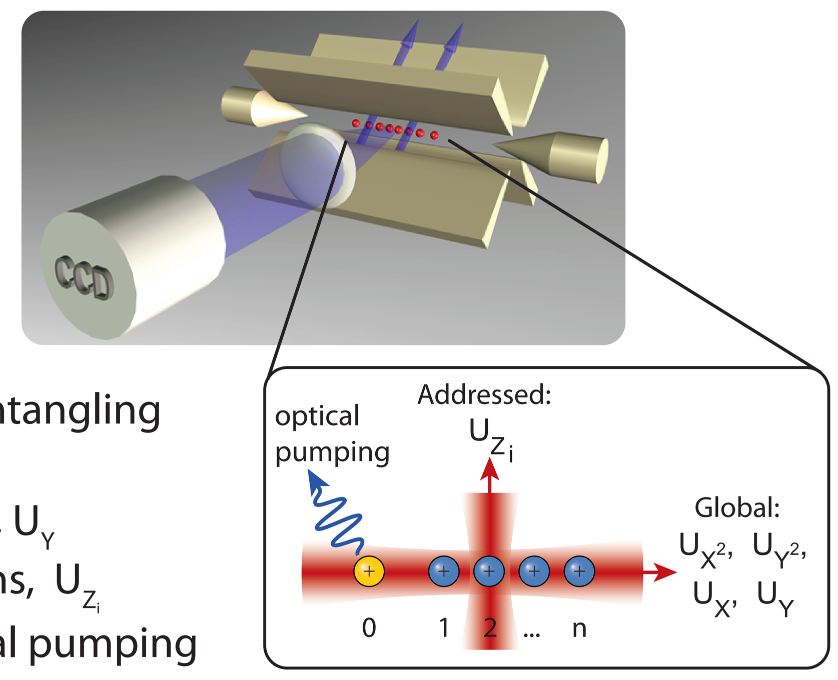
What? "Pumping" of arbitrary initial states (mixed states) into entangled states (Bell and GHZ states).
Simulation of coherent many-body spin interactions.
Quantum non-demolition measurement of multi-qubit observables.

Where?

Linear string of 3-5 trapped ions

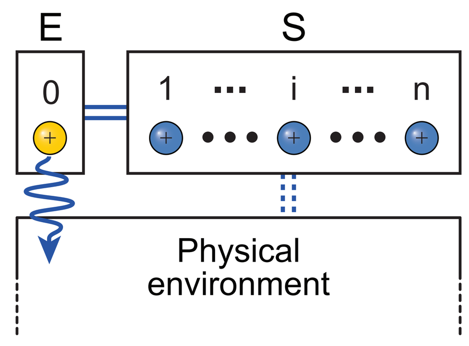
Tools?

(i) Mølmer-Sørensen entangling operation, U_{X^2}, U_{Y^2}
(ii) Global rotations, U_X, U_Y
(iii) Single-qubit rotations, U_{Z_i}
(iv) Dissipation by optical pumping

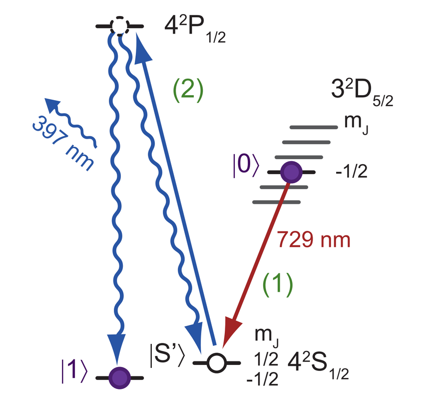


Engineered dissipation

Divide ions into system qubits (S) and environment qubits (E).



Reset of environment qubits.



(1) transfer population to |S'⟩
(2) optical pumping to |1⟩

Engineering open-system dynamics

Goal: Model dissipation term of the master equation (Lindblad operator)

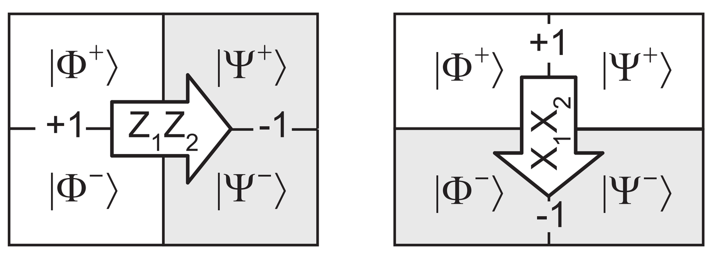
$$\frac{d}{dt}\rho = -\frac{i}{\hbar}[H,\rho] + \mathcal{L}(\rho)$$

with

$$\mathcal{L}(\rho) = \frac{\gamma}{2}(2c\rho c^\dagger - c^\dagger c\rho - \rho c^\dagger c)$$

Example: Design dissipative dynamics that pumps arbitrary input state into Bell state $|\Psi^-\rangle$.

The idea: Use two maps that pump from +1 to -1 eigenspace of the stabilizer operators Z_1Z_2 and X_1X_2



For stabilizer Z_1Z_2 use the map

$$\epsilon(\rho_S) = E_1\rho_S E_1^\dagger + E_2\rho_S E_2^\dagger$$

with

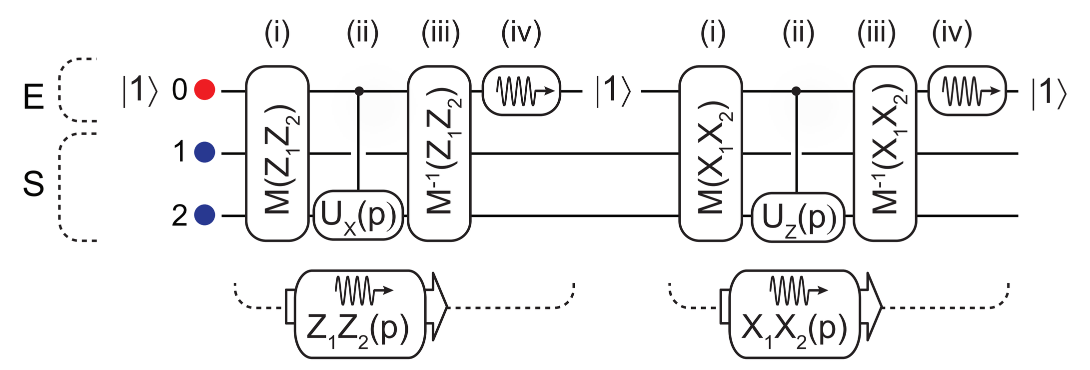
$$E_1 = \sqrt{p}X_2\tfrac{1}{2}(1+Z_1Z_2)$$
$$E_2 = \tfrac{1}{2}(1-Z_1Z_2) + \sqrt{1-p}\tfrac{1}{2}(1+Z_1Z_2)$$

and p the probability for mapping into the -1 eigenspace.

The repeated application of this map for p<<1 is equivalent to simulating the dissipative dynamics of the Lindblad operator

$$c_1 = \tfrac{1}{2}X_2(1+Z_1Z_2)$$

Experimental realization:
(i) Use the operation $M(Z_1Z_2)$ to map the +1 (-1) stabilizer information of qubits 1 & 2 onto the |0⟩ (|1⟩) state of the ancilla qubit 0 (initially in |1⟩)



(ii) Apply the controlled gate operation

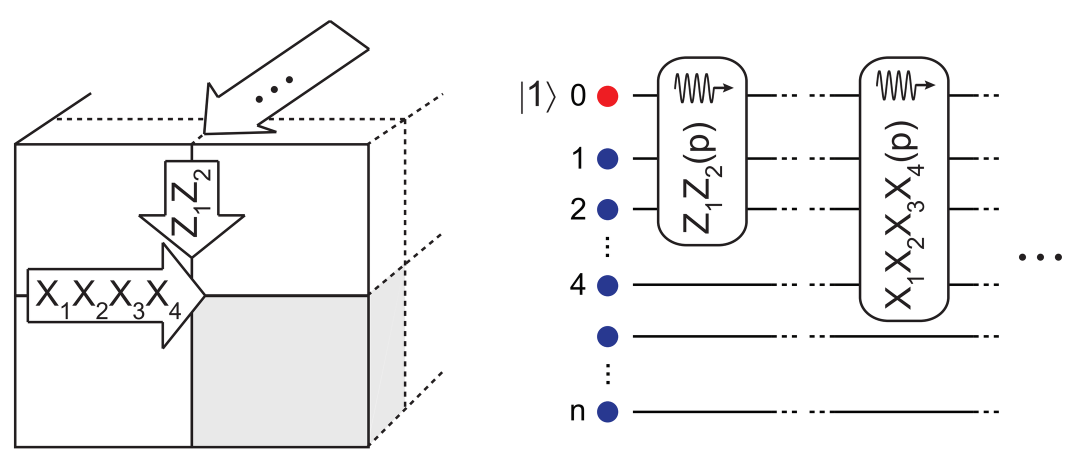
$$C(p) = |0\rangle\langle 0|_0 \otimes U_{X_2}(p) + |1\rangle\langle 1|_0 \otimes 1$$

to map to the +1 eigenspace of the stabilizer with probability p.

(iii) Invert the initial mapping, $M^{-1}(Z_1Z_2)$.

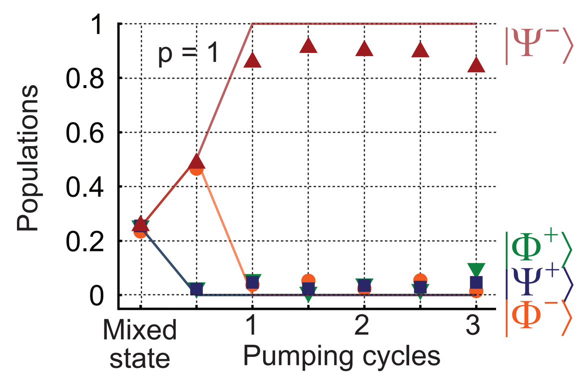
(iv) Reset the ancilla qubit to repeat pumping with stabilizer X_1X_2. This step carries away entropy to 'cool' the system qubits into the Bell state.

In analogy, we engineer dissipative maps for n-qubit stabilizer pumping.

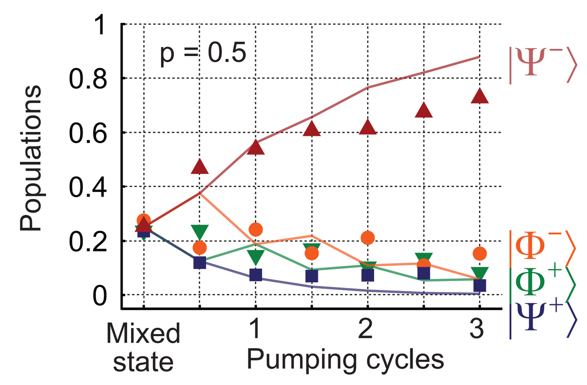


Experimental Bell-state pumping

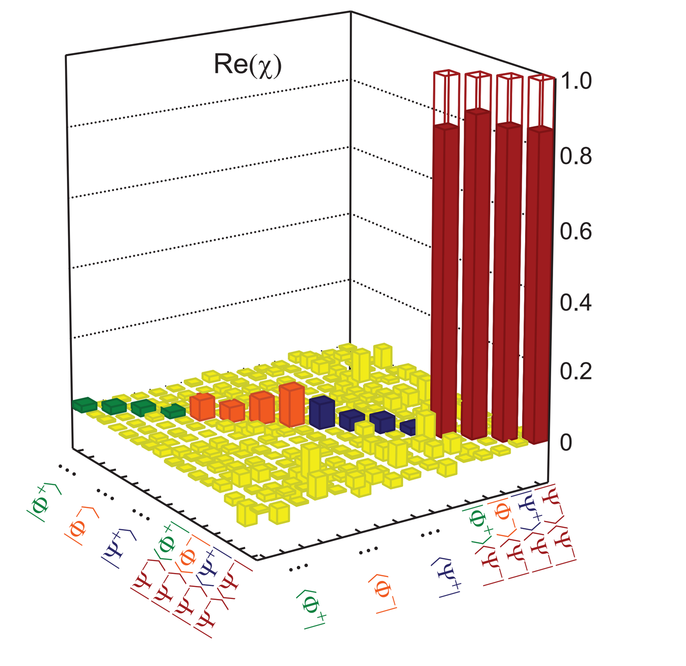
Deterministic (p=1)



Probabilistic (p=0.5)

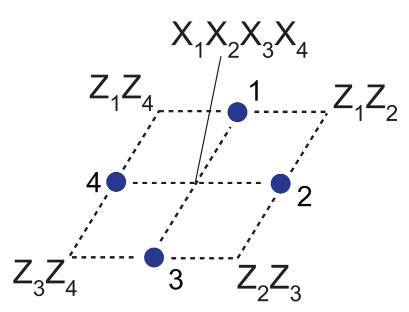


Reconstructed process matrix (p=1, after 1.5 cycles)



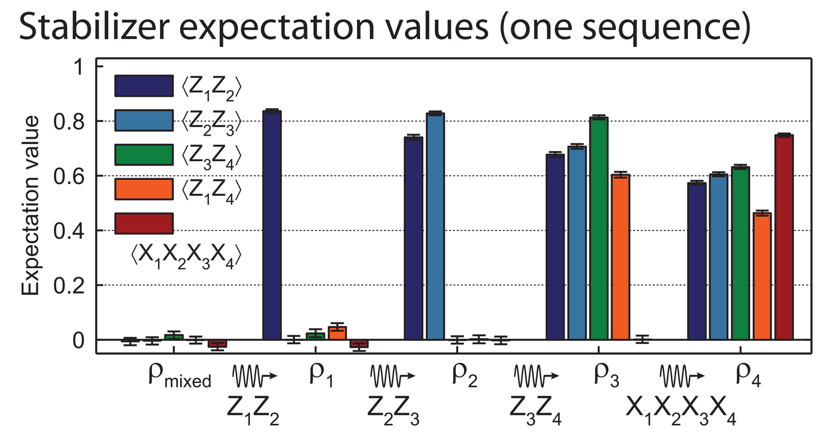
- Mixed initial state is pumped into Bell state.
- p=0.5 towards dynamics of a master equation.
- Gate errors lead to steady-state loss of fidelity ~ ε / p

Four-qubit stabilizer pumping

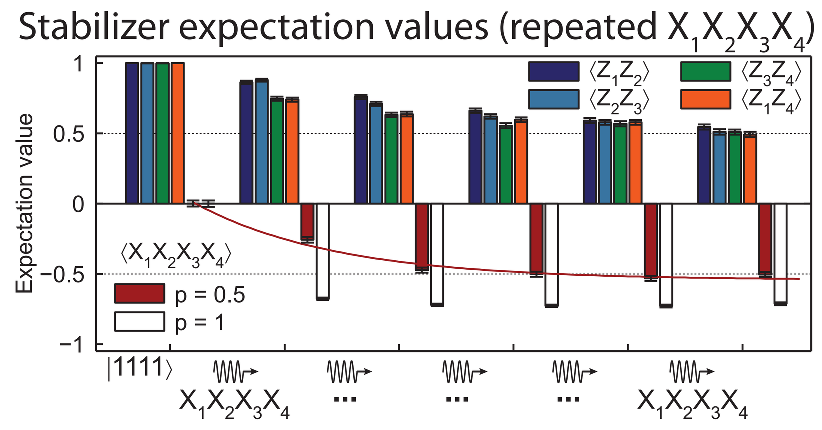


- Sequential pumping of stabilizers Z_1Z_2, Z_2Z_3, Z_3Z_4, and $X_1X_2X_3X_4$.
- Populations of pairwise antiparallel spin states (-1 eigenspace of stabilizer Z_iZ_j) disappear after pumping into +1 eigenspace.
- Final pumping of $X_1X_2X_3X_4$ stabilizer builds up coherence.

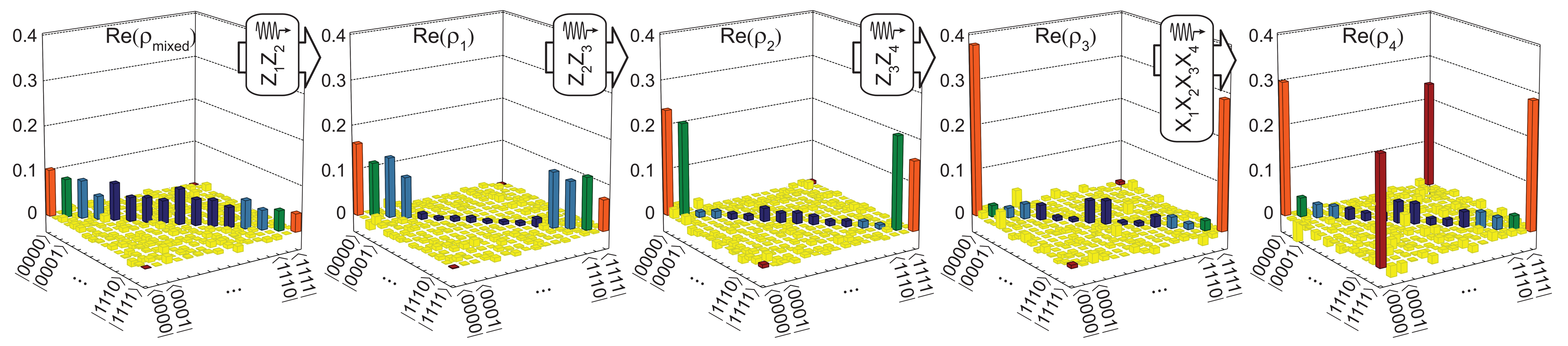
Stabilizer expectation values (one sequence)



Stabilizer expectation values (repeated $X_1X_2X_3X_4$)

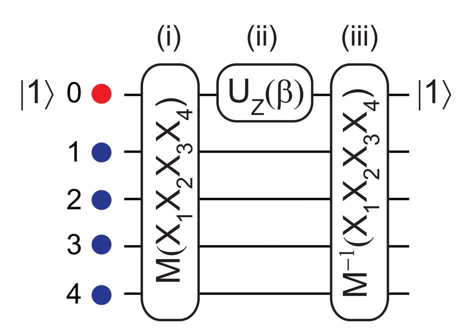


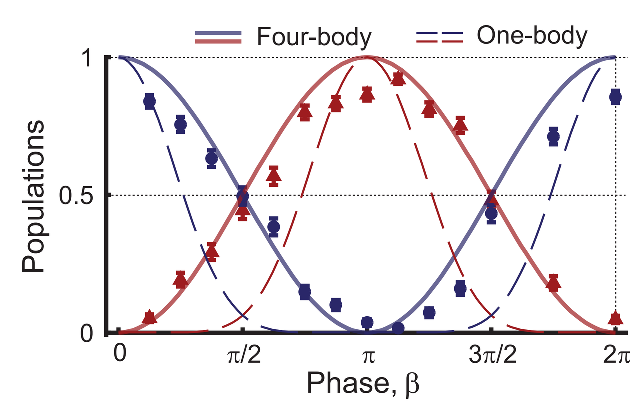
Density matrix evolution during pumping



Coherent many-body interactions

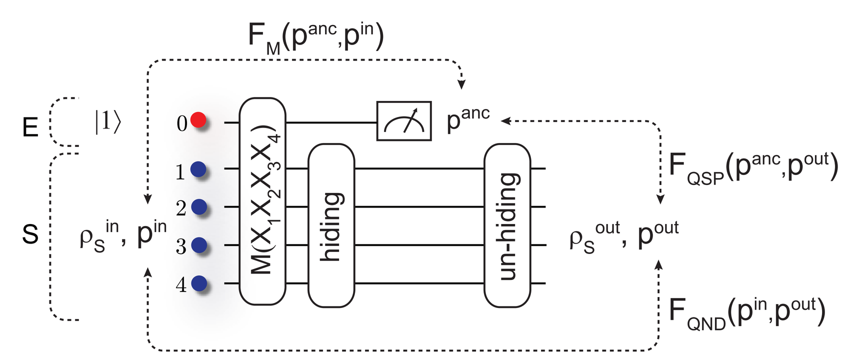
Example: four-qubit





(i) $M(X_1X_2X_3X_4)$ maps stabilizer state onto ancilla.
(ii) +1 (-1) stabilizer states experience phase rotation β/2 (-β/2).
(iii) Reverse step (i).
Effectively simulates 4-qubit Hamiltonian $H=-g\,X_1X_2X_3X_4$ with $\beta=2\,g\,\tau$.

QND stabilizer measurement



Quantum non-demolition (QND) measurement of 4 qubit stabilizer.
Quantum non-demolition fidelity: F_{QND}=96.9(6)%
Quantum state preparation fidelity F_{QSP}=73(1)%

Conclusion and outlook

- Toolbox for simulating open-system dynamics.
- Simulate general Markovian dynamics by adding classical feedback.
- Driven dissipative quantum phase transitions.

Literature

[1] H. Krauter, et al., arXiv:1006.4344 (2010); S. Diehl, et al., Nature Phys. 4, 878 (2008); J. Cho, et al., arXiv:1008.4088 (2010).
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