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High-fidelity mixed-species entangling gates

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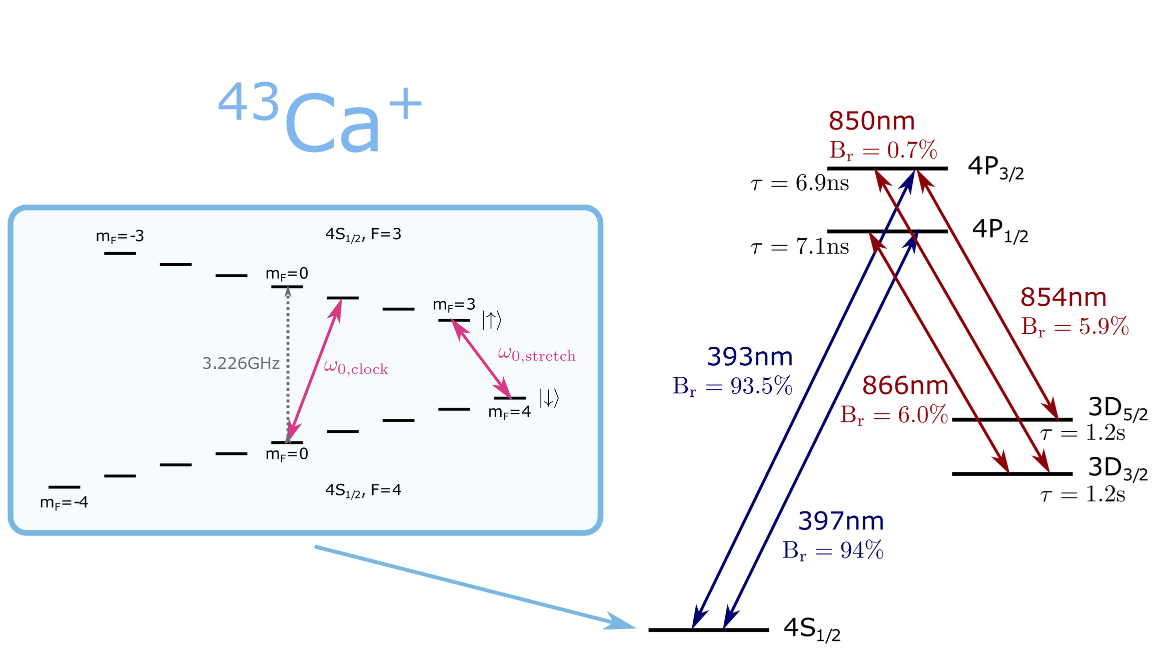
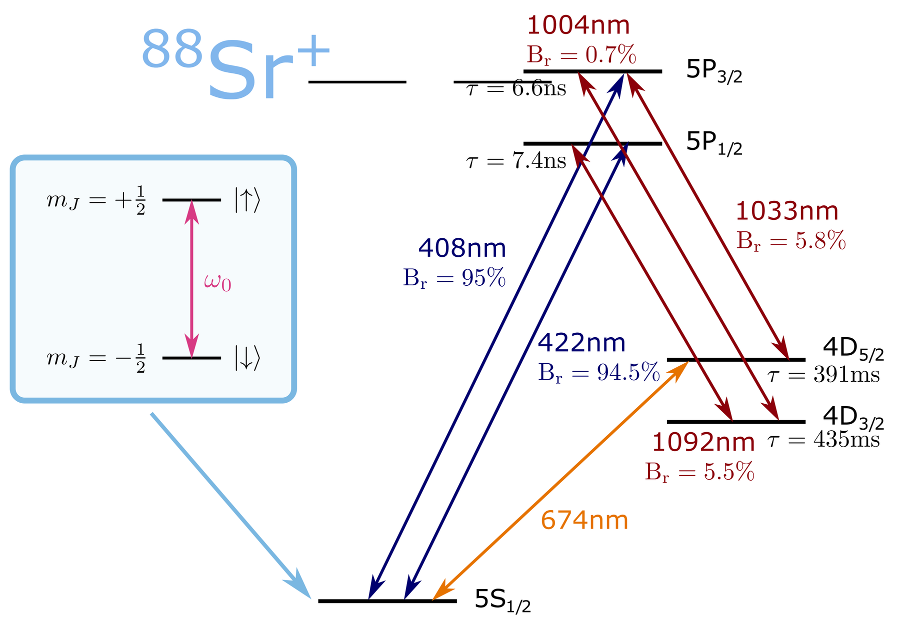
Trapped ions are a promising candidate for building a quantum computer - the qubits have long coherence times, and state-preparation, readout, single- and two-qubit operations have all been demonstrated with high fidelities, above the threshold for quantum error correction.
However, increasing the number of qubits without increasing errors at the same time is challenging. A promising approach for scaling up trapped-ion quantum computers is to network many small ion-trap nodes via photonic links. A key ingredient in this scheme is the combination of different atomic species: this allows sympathetic cooling of the ion crystal, as well as excitation of ions of one species to emit entangled photons without corruption of the electronic state of the memory or logic qubits. Entangling gates between the different species of ion are a central step in this scheme. We present two-qubit gates between $^{43}Ca^+$ and $^{88}Sr^+$ with fidelity F = 99.5(3)%, pushing mixed-species gate fidelities closer towards the best single-species gates.
We further show how to use this gate operation to enhance the coherence time of the $^{88}Sr^+$ qubit. Finally we demonstrate a first characterisation of our mixed-species gate operation using two-qubit randomised benchmarking.

The qubits

- hyperfine qubit in $^{43}Ca^+$ at 146G, stretch qubit $T_2^* \approx 5$ms, clock qubit $T_2^* \approx 50$s, qubit frequencies ≈ 3 GHz
- Zeeman qubit in $^{88}Sr^+$ at 146G, qubit frequency 408.7 MHz
- state-preparation and readout errors $\approx 1.2 \cdot 10^{-3}$
- single-qubit operations in Ca can be driven by microwaves or pair of Raman lasers; in Sr by rf or 674nm quadrupole laser



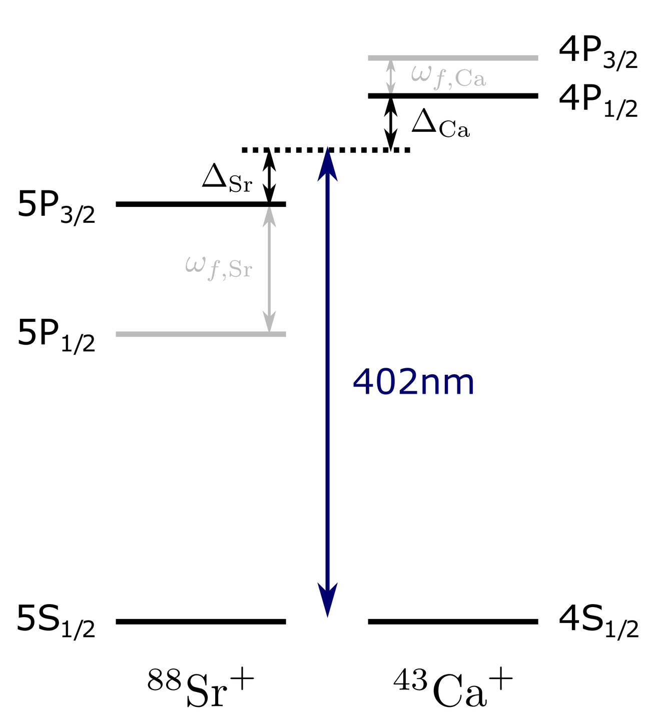
- two-qubit operations driven by pair of Raman lasers
- entangling gate performed on axial modes
- in-phase mode freq 1.51MHz, Lamb Dicke factor Ca: 0.089
- out-of-phase mode freq 2.94MHz, Lamb Dicke factor Ca: 0.126

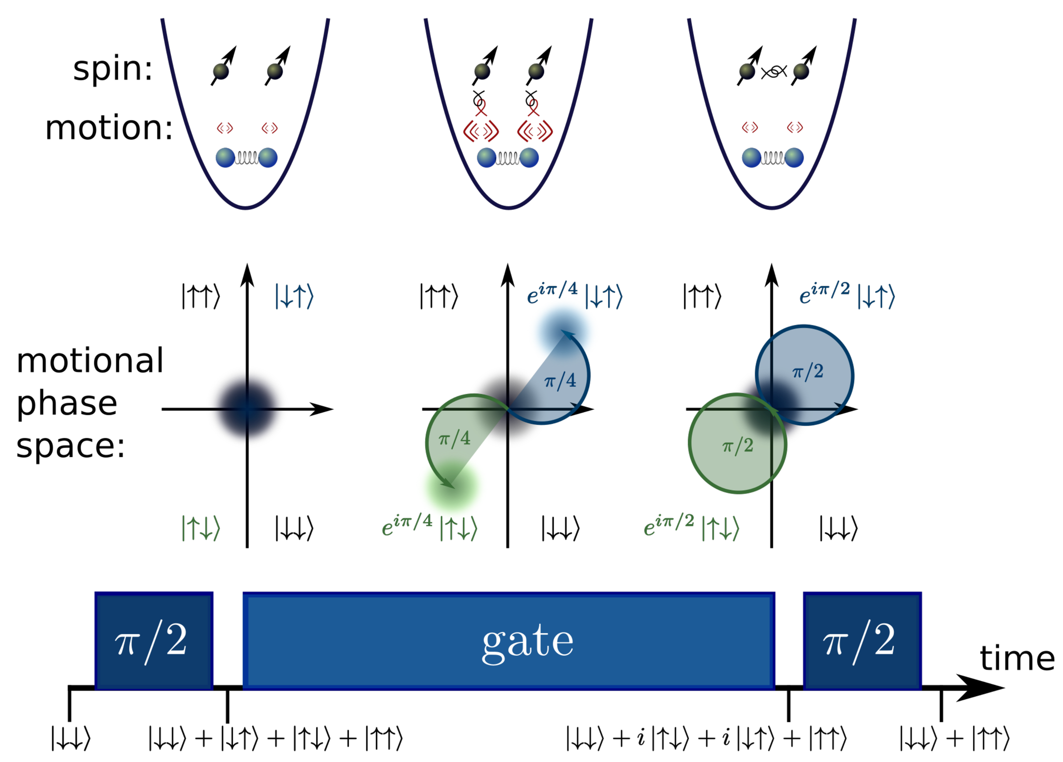


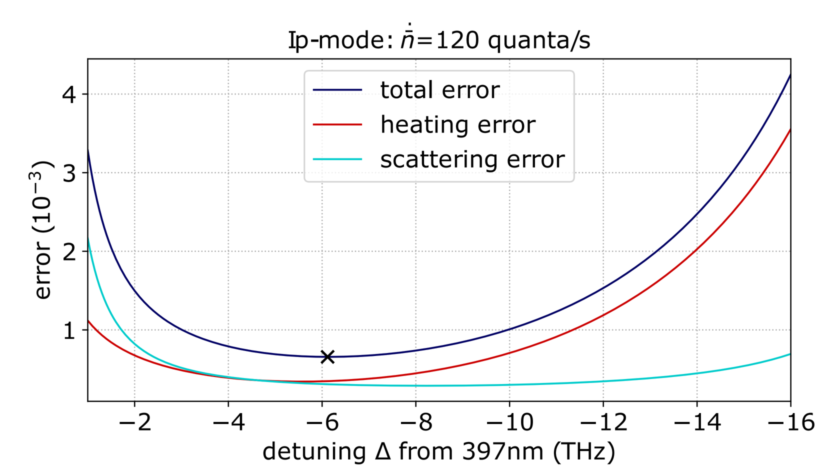
$^{43}Ca^+$-$^{88}Sr^+$ entangling gates

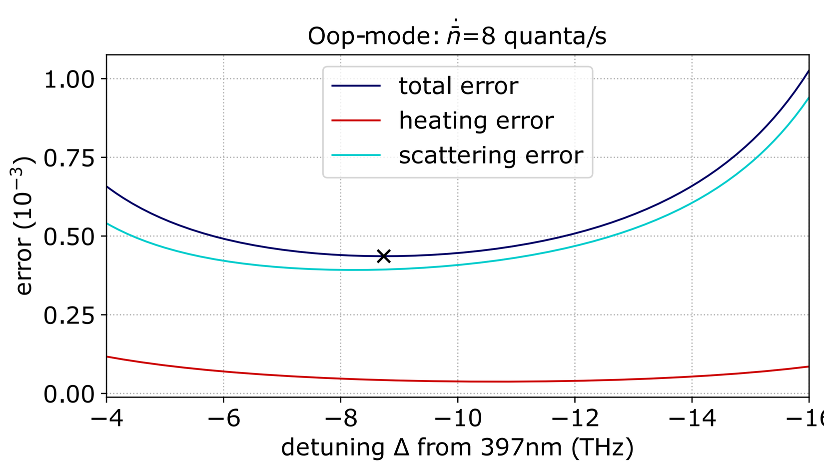
Gate mechanism

- σ_z geometric phase gate performed with pair of Raman lasers
- can use single pair of Raman lasers to perform gate on both qubit species simultaneously
- both Raman beams derived from single frequency-doubled Ti:Sapphire laser



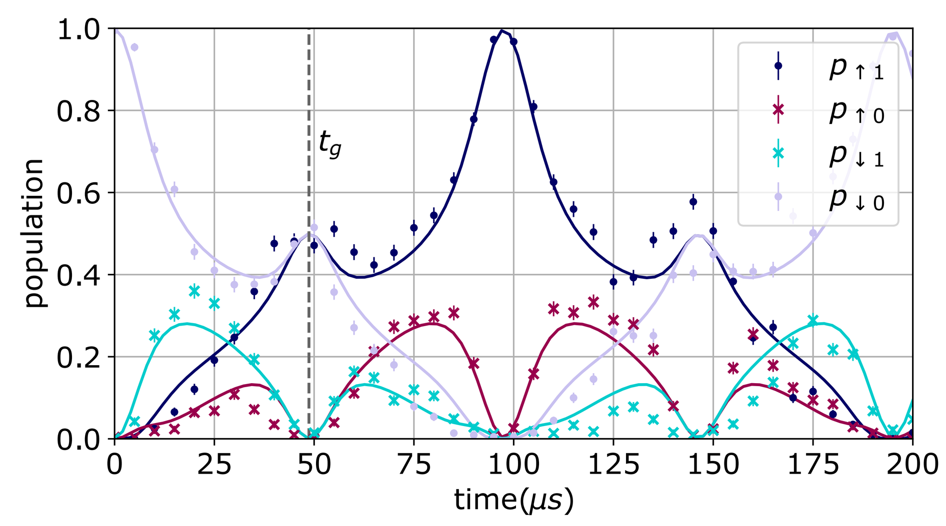


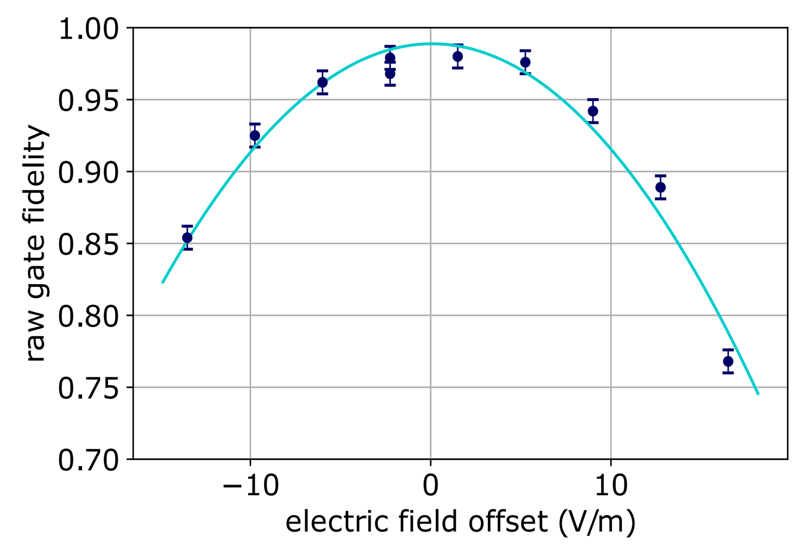




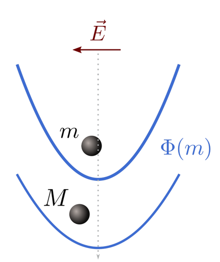
- trade-off between errors due to ion heating and photon scattering
- finite Raman power means heating error smaller for smaller Raman detunings
- photon scattering smaller for larger/symmetric Raman detuning

Results

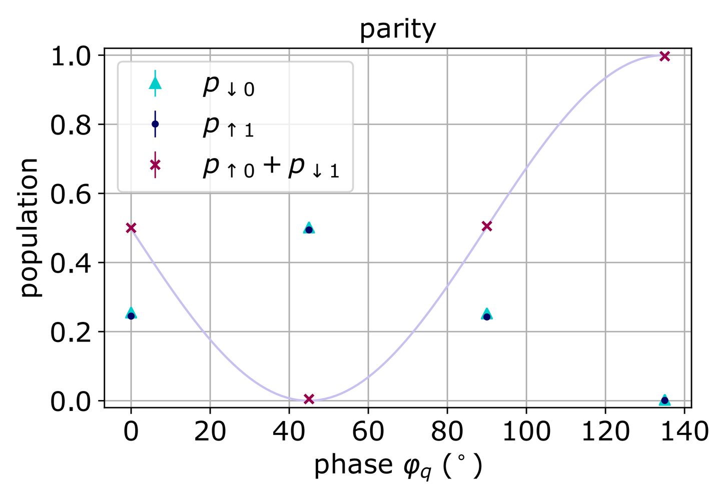


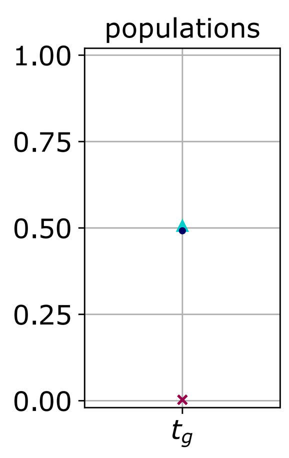


- asymmetric forces on $^{43}Ca^+$ and $^{88}Sr^+$ cause asymmetry in $p_{\uparrow 0}$ and $p_{\downarrow 1}$ traces
- asymmetry of Rabi frequency also makes gate less efficient, because part of the geometric phase becomes a global phase ($I \otimes I$) rather than a two-qubit phase ($\sigma_z \otimes \sigma_z$)



- gate fidelity highly sensitive to trap compensation, due to crystal tilt
- typical drift of trap compensation voltages: ~7V/m per month



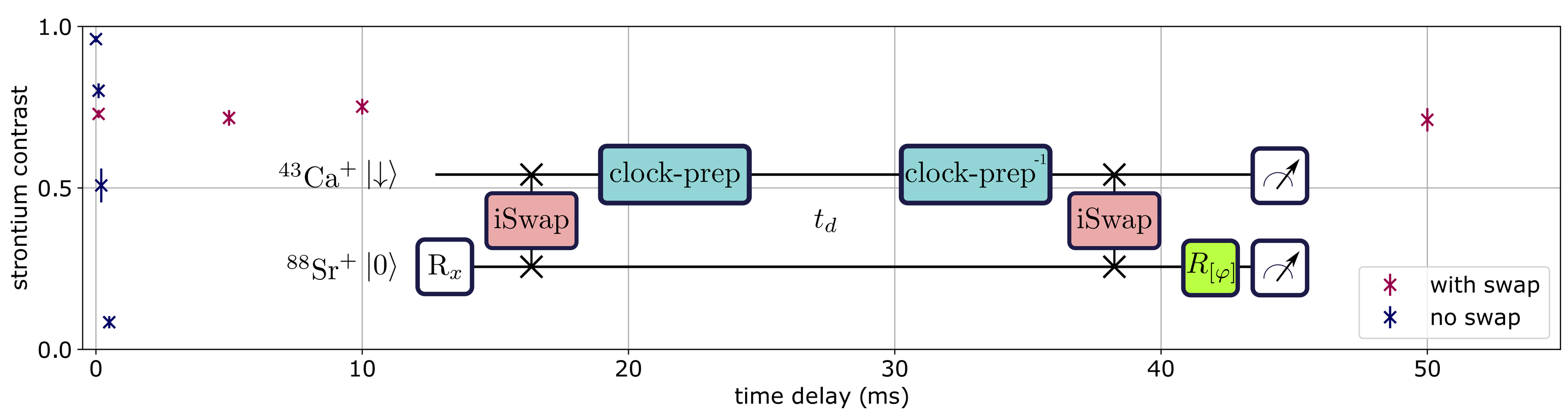


- preliminary best gate fidelity F=99.5(3)% after normalising SPAM errors
- fidelity estimated directly from parity of quadratures, without fitting

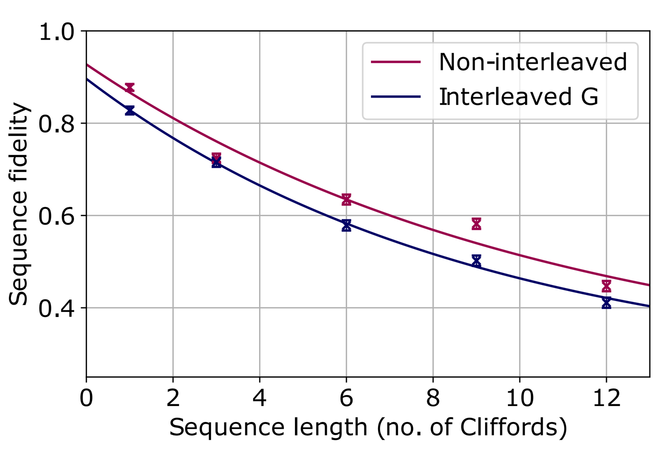
$$\mathcal{F} = \frac{1}{2}(\text{population} + \text{parity})$$

$$\text{par} = [p_{\downarrow 1} + p_{\uparrow 0}]_{\varphi_{q,1}} - [p_{\downarrow 1} + p_{\uparrow 0}]_{\varphi_{q,2}}$$

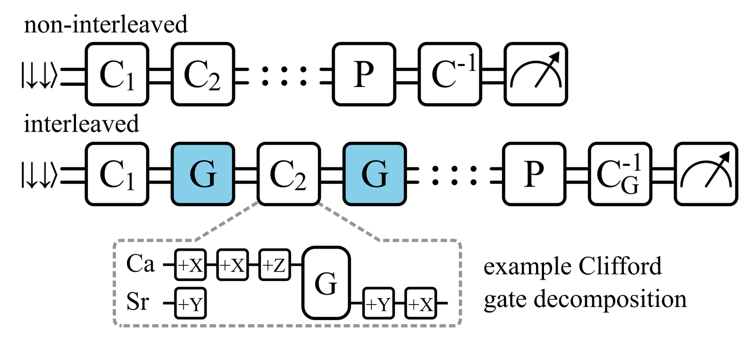
Outlook



- Sr state can be mapped onto Ca clock qubit with swap gates for longer memory
- errors dominated by magnetic field noise during clock-state preparation



- preliminary two-qubit randomised benchmarking results: error per entangling gate = 1.2(10)%
- error per two-qubit Clifford operation = 6.7(7)% (on avg 1.5 entangling gates + 7.7 single-qubit operations)
- this data limited by errors due to magnetic field noise



- two-qubit Cliffords with or without interleaved gates (G), followed by an inverting operation
- randomly-chosen π-pulses (P) to average over measurement outcomes

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