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High-fidelity mixed-species entangling gates

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Working with mixed-species ion crystals is very important for scaling up trapped ion systems for quantum computing and networking. A high-fidelity entangling gate between ions of different species gives the freedom to select ions with preferable attributes for different tasks, and to coherently map the information from one to the other depending on the required task.
We present a Mølmer-Sørensen gate entangling a $^{43}Ca^+$ and a $^{88}Sr^+$ ion using bichromatic Raman laser beams which are near-resonant with qubit transitions in the hyperfine manifold and in the Zeeman-split levels respectively.

We measure a Bell-state fidelity of 99.6(2)%, which is close to the fidelity previously obtained using a mixed-species $\sigma_z \otimes \sigma_z$ light-shift gate in the same experimental setup (99.8(2)% [1]).
The comparison between the two gates allows selection of the more robust mechanism for use in a future networking experiment. The advantage of the Mølmer-Sørensen mechanism is that it can be used on first-order field-insensitive 'clock' qubit transitions, which appear in $^{43}Ca^+$. However, we find that the mixed-species Mølmer-Sørensen gate is far more sensitive to slow drifts in the magnetic field than the light-shift gate.

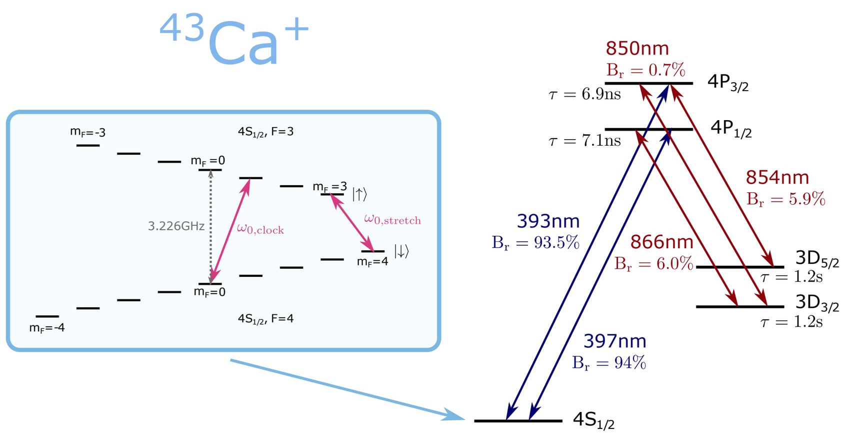
The qubits

- Hyperfine qubit in $^{43}Ca^+$ at 146 G, stretch qubit T2* ≈ 5 ms, clock qubit T2* ≈ 50 s, qubit frequency 3.2 GHz

- Clock-qubits are magnetic-field insensitive in the first order and enable long coherence times

- Zeeman qubit in $^{88}Sr^+$ at 146 G, qubit frequency 408.7 MHz

- Mass ratio ≈ 2

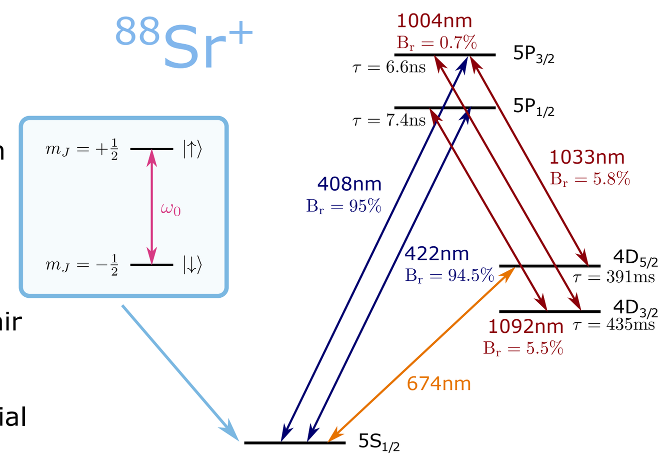


- State-preparation and readout errors ≈ 1.2 × 10^{-3} (average over both species)

- Single-qubit operations in each ion can be performed using a pair of Raman lasers or microwaves

- Two-qubit operations driven by pair of Raman lasers

- Entangling gate performed on axial modes

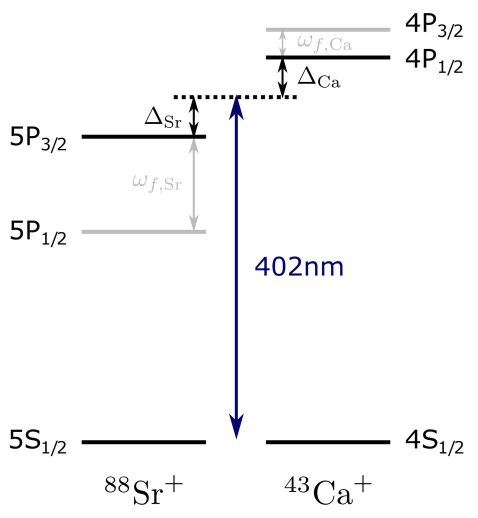


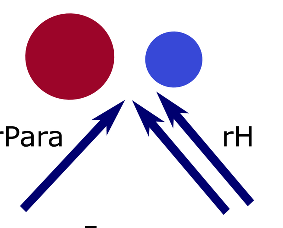
$^{43}Ca^+$-$^{88}Sr^+$ entangling gates

Gate mechanism

- Mølmer-Sørensen gate - simultaneously applying red and blue sideband interactions that are symmetrically detuned from the qubit resonance

- Use Raman transitions (one Raman beam is shared between the two species)

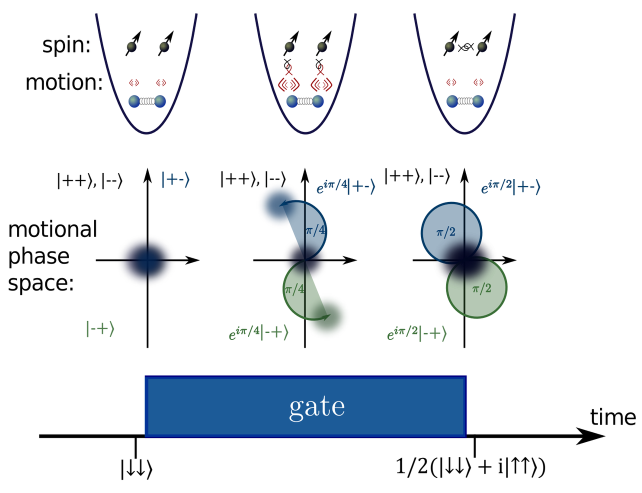




$\omega_b = \omega_L - \omega_z - \delta$
$\omega_r = \omega_L + \omega_z + \delta$

$\omega_L + \omega_{Ca}$
$\omega_L + \omega_{Sr}$

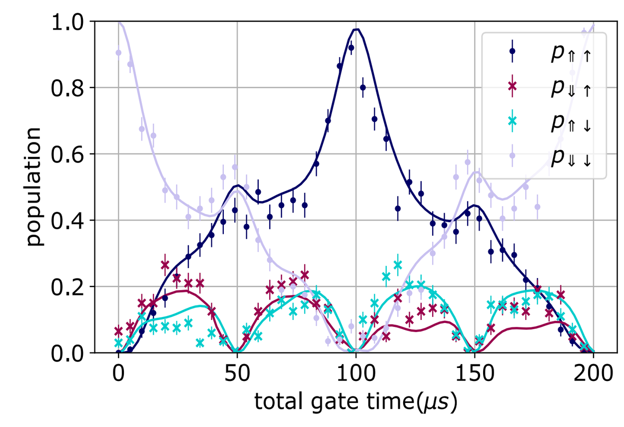
- both Raman beams derived from single frequency-doubled Ti:Sapphire laser



- The spin-dependent force is acting on the rotated basis, |+⟩, |-⟩, eigenstates of σ_ϕ

- By choosing an appropriate gate detuning (δ) and interaction duration, the spin and the motion become disentangled at the end of the gate, but the ion spin states are left in a maximally entangled state

Results



- Mølmer-Sørensen gate on the magnetically sensitive qubit, F=4, m_F=4 and F=3, m_F=3 in $^{43}Ca^+$ and Zeeman qubit in $^{88}Sr^+$

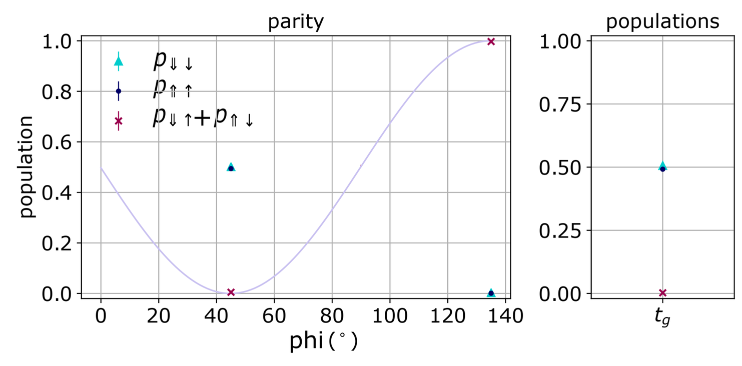
- Asymmetric forces on $^{43}Ca^+$ and $^{88}Sr^+$ cause asymmetry in $p_{\Uparrow\downarrow}$ and $p_{\Downarrow\uparrow}$ traces

- The asymmetry is dominated by the power mismatch between the two rH beams, which were tuned to be similar in power

- Gate fidelity 99.6(2)% after state preparation and readout error normalisation

- Fidelity estimated directly from two-point parity measurement, without fitting

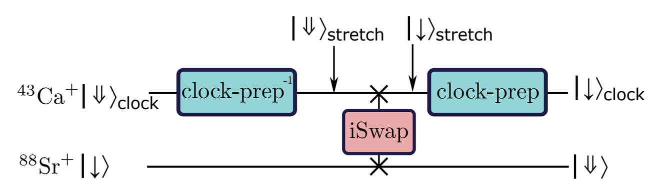
- Parity is defined as $\langle \hat{\sigma}_{z,1}\hat{\sigma}_{z,2}(\text{phi}) \rangle$



Light-Shift vs Mølmer-Sørensen

- Sr state can be mapped onto Ca clock qubit with swap gates for longer memory

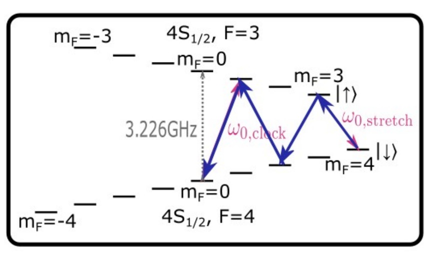
Light-shift gate



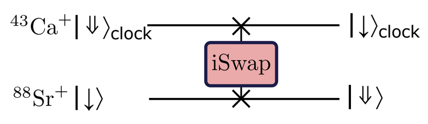
- Previous work in our group demonstrated a mixed-species light-shift gate - high fidelity 99.8(2)%

- The light-shift gate relies on a differential AC Stark-shift produced across the qubit transition by the electric dipole interaction -> not easy to apply it to clock qubits due to the strongly supressed Rabi frequency

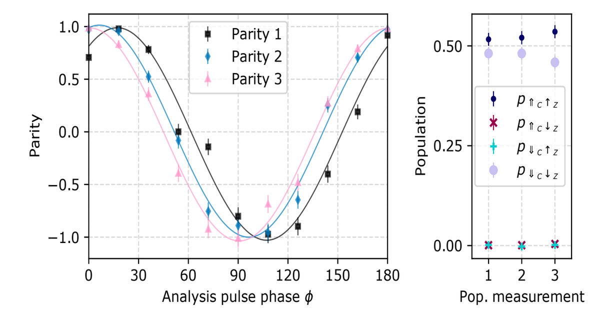
- Do gate on the stretch qubit, then transfer the population to the clock qubit -> not free of errors as a result of the magnetic field noise



Mølmer-Sørensen gate



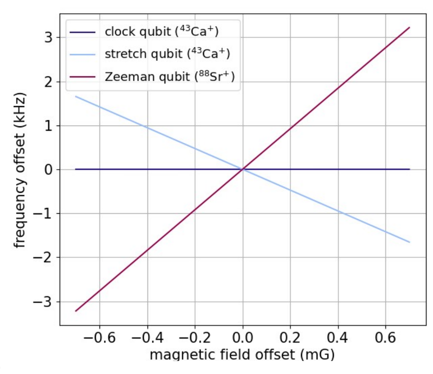
- Can apply the MS gate directly to clock qubits; however very sensitive to slow drifts in the magnetic field



- This suggests a change in the phase of the created Bell state from run to run

- This effect is supressed when applying the gate on the stretch qubit instead of the clock qubit in Ca

- Similar frequency offsets due to magnetic field drift cancel out in this case as a result of the almost equal-and-opposite magnetic field sensitivities



[1] Hughes, A. C., et al. "Benchmarking a high-fidelity mixed-species entangling gate." (2020)

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