Deterministic Entanglement of Trapped-Ion Spin-Qubits

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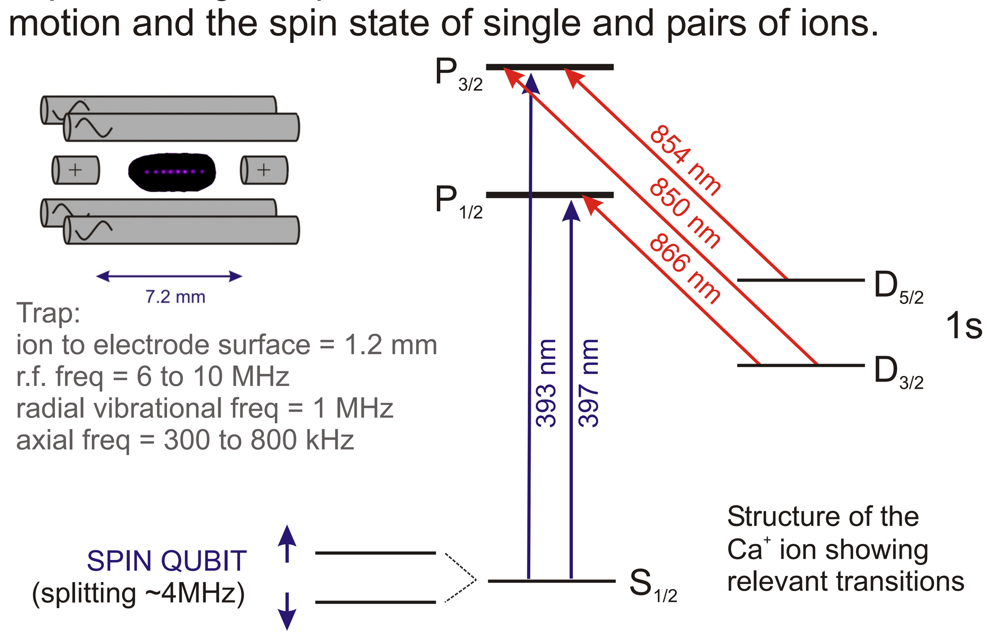
Main points

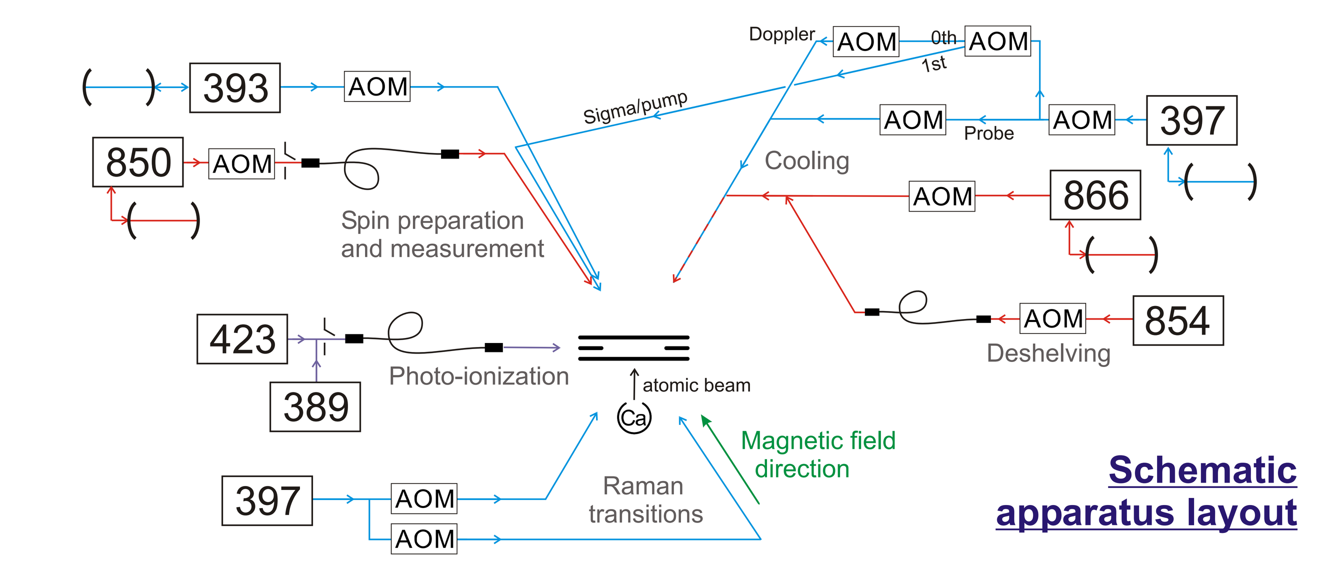
The quantum state of a group of trapped ions can be manipulated and measured with high precision using laser cooling techniques. This allows the system to realize quantum information processing. We present experiments implementing complete coherent control of the harmonic motion and the spin state of single and pairs of ions.



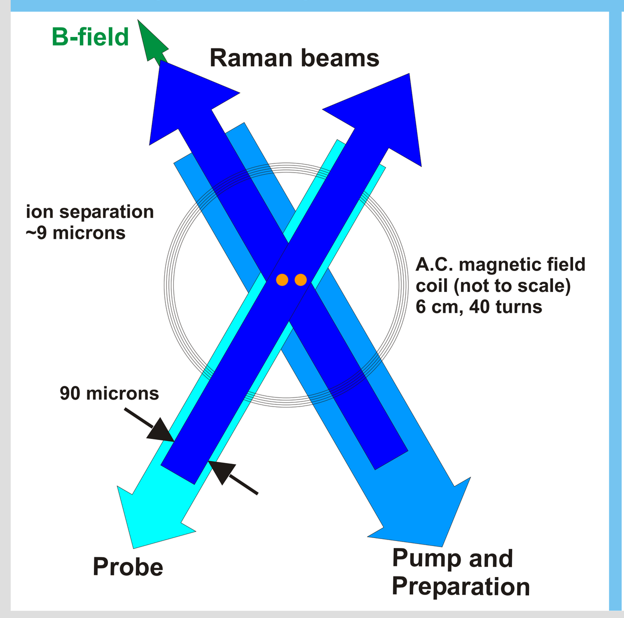
Experimental studies:

- single-ion coherent manipulations such as Rabi flops, Ramsey and spin-echo sequences with up to 98% fidelity
- cooling of a single ion to ground state in one dimension by three varieties of Raman sideband cooling, <n>=0.02
- cooling of both axial modes of an ion pair close to ground state
- motional heating rate <2 phonon/s (best), <10 phonon/s (typical)
- motional coherence time ~100 ms
- Schrödinger cat states of a single ion, up to $\langle n \rangle = |\alpha|^2 = 9$
- **Deterministic entanglement of two ions, with 75% fidelity**

Experimental details

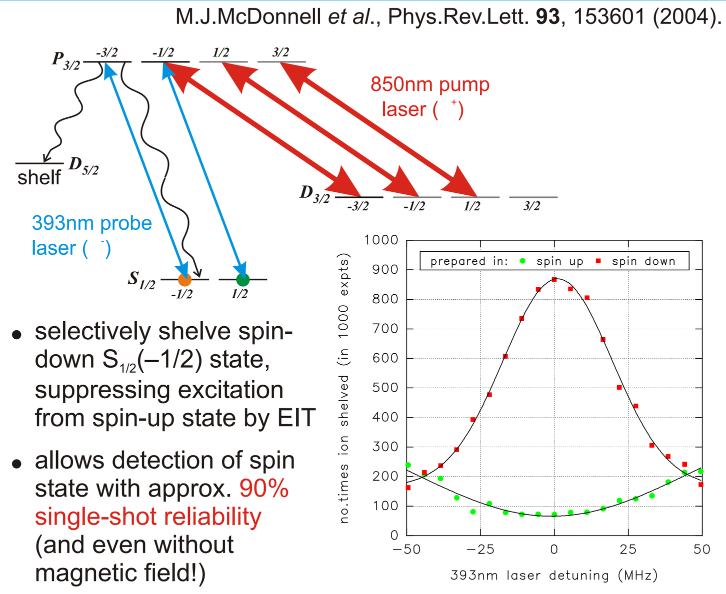


Cooling and Logic Laser Beams



Qubit state readout method

M.J.McDonnell *et al*., Phys.Rev.Lett. **93**, 153601 (2004).



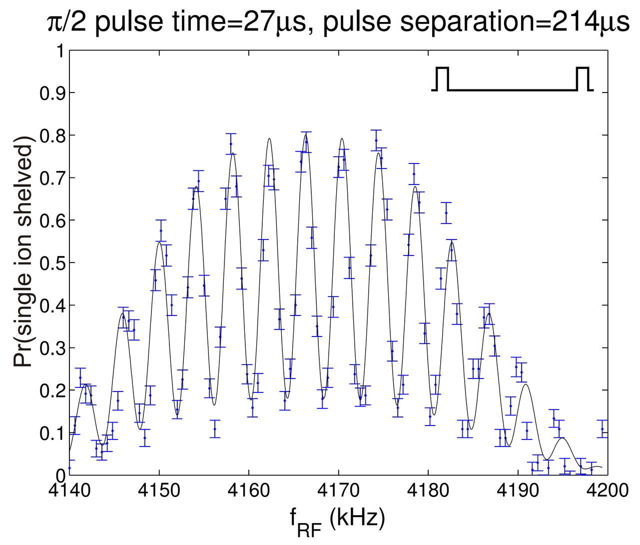
- selectively shelve spin-down $S_{1/2}(-1/2)$ state, suppressing excitation from spin-up state by EIT
- allows detection of spin state with approx. 90% single-shot reliability (and even without magnetic field!)

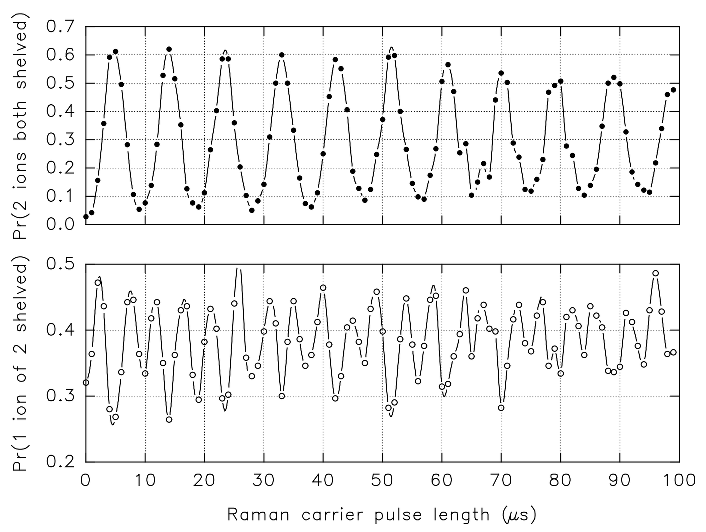
Single-qubit gates, 1-2 ions

Raman beams resonantly excite the two-photon transition between qubit levels, and provides coherent manipulation of the spin qubit state.

Single-ion Ramsey fringes

The qubit transition can also be driven by a radio-frequency (RF) magnetic field. Here the pulse needed to achieve full inversion is split into two with a delay between them - a form of "Young's slit" experiment. Interference fringes are seen as the RF frequency is scanned.





Two-ion Rabi oscillations

2-ion spin-state = 2 qubits. Rabi flopping, here driven by the Raman transition (4.5 μs π time), gives a single-qubit rotation applied to both qubits simultaneously.

EIT readout ⇒ 0,1 or 2 ions shelved
infer P(↓↓), P(↑↓)+P(↓↑), P(↑↑)

Ground state cooling

The motional state of the string of ions acts as an extra degree of freedom that can be used to couple the ions together coherently. In order to use the modes of vibration of the ion strings as a quantum "bus" the ions must be cooled to the ground state of the trapping potential.

Cooling is performed in three stages:

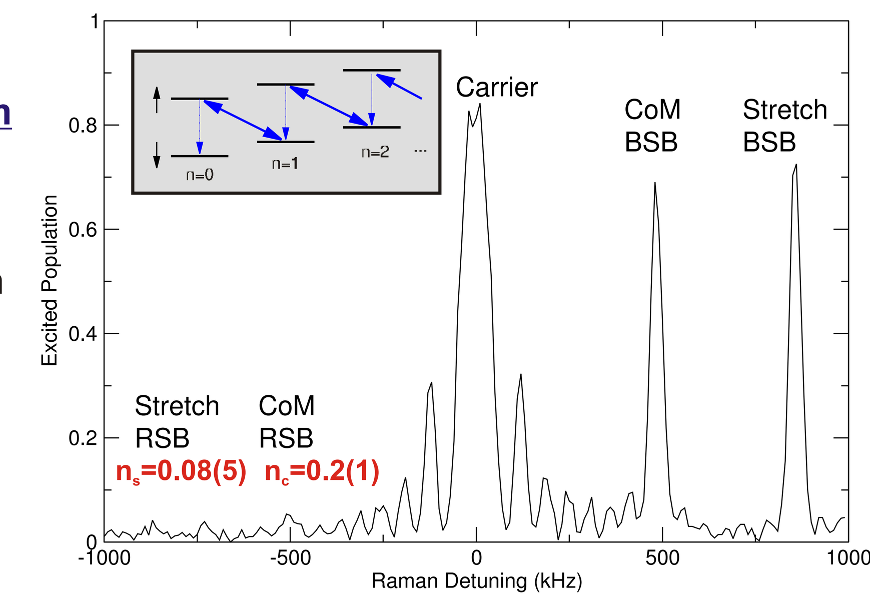
- Doppler cooling ⇒ <n> ≈ 500 K
- Continuous Raman sideband cooling ⇒ <n> ≈ 1
- Pulsed Raman sideband cooling ⇒ <n> ≈ 0

The final ion temperature can be obtained from the ratio of the red sideband (RSB) height to the blue sideband (BSB) height for a given mode of vibration.

For a single ion, we achieve <n>=0.02(1), in an 820kHz trap, giving T=10 μK.

Two-ion Raman spectrum

0.2ms Doppler cooling
6ms continuous Raman
2x20 cycles pulsed Raman

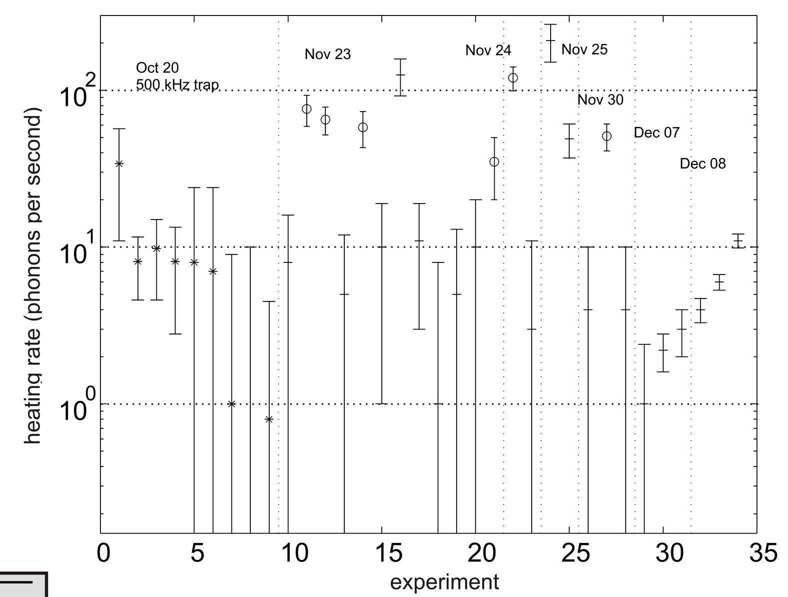


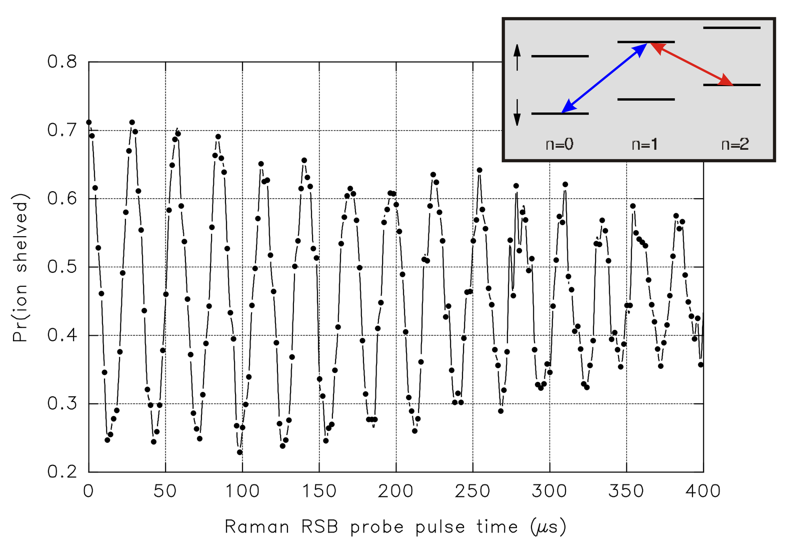
Heating and motional decoherence

Single-ion heating rate measurements

Method: cool to the ground state, wait 10-50ms, measure temperature by sideband strengths.
Circled points: with weak laser heating

Results: <2 phonon/sec (best)
<10 phonon/sec (typical)
(but occasionally anomalously high!)



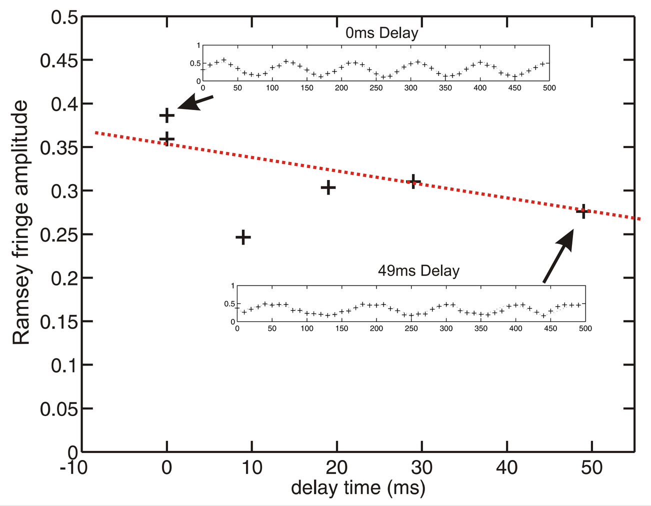


Fock state creation

Single ion is first transferred from (↓,n=0) to (↑,n=1) with a BSB π-pulse, then we observe flopping on the (↑,n=1) (↓,n=2) transition by driving the RSB.
observed $\Omega_{n=2 \to 1} / \Omega_{n=1 \to 0} = 1.5$

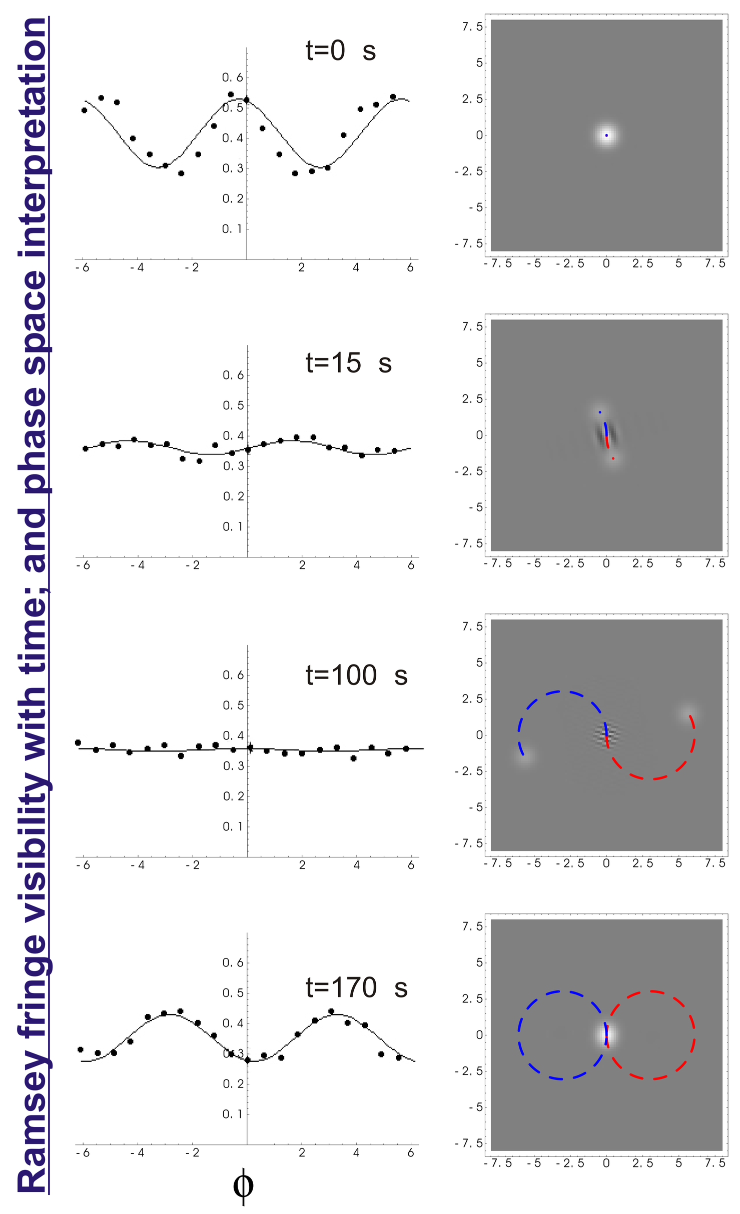
Motional decoherence

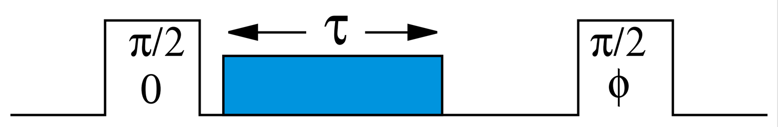
A "Ramsey" experiment on the *motional* state: carrier π/2, RSB π ⇒ superposition of (↓,n=0)+(↓,n=1) vibrational levels, wait, reverse the superposition while scanning the phase of the final π/2 pulse. Fringe contrast measures coherence time.



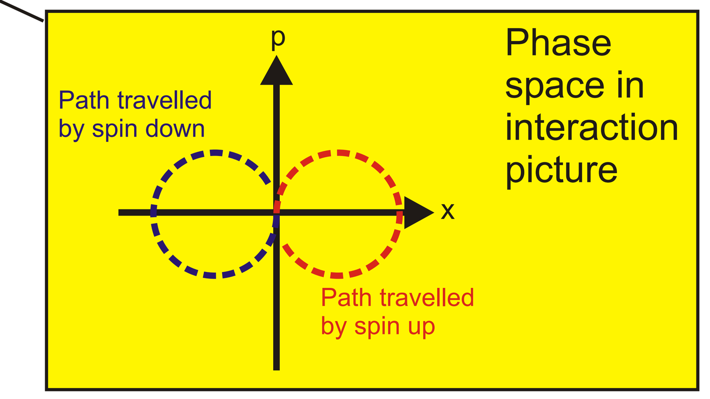
Schrödinger Cat states

Glauber *coherent states* of a harmonic oscillator approximate to classical motion, and a superposition of such states at mesoscopic excitation <n> is a type of Schrödinger cat. We create such mesoscopic superpositions of the motion of a single ion, with the spin state playing the role of measuring device entangled with the motion. We prove the 'cat' maintains its coherence by bringing the two parts back together and observing an interference. [As first demonstrated by Monroe *et al.* Science 272 1131 (1996).]

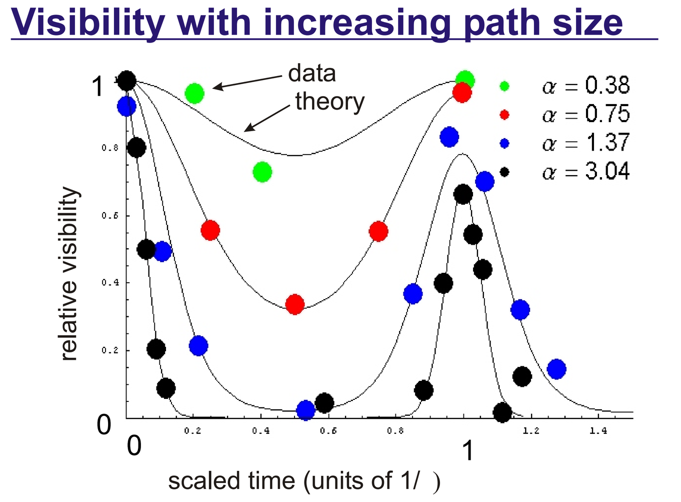




The motion is driven into coherent states by applying an oscillating spin-dependent driving force from a laser standing wave.



Visibility with increasing path size



Deterministic entanglement

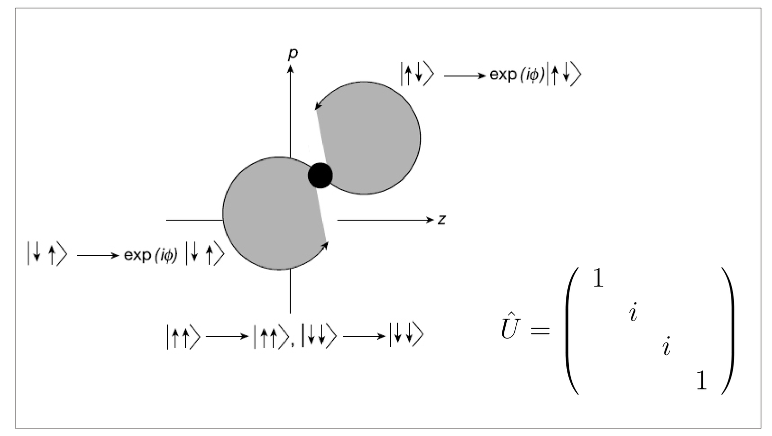
Quantum entanglement occurs when the state of a system cannot be reduced to a product of the states of the component parts of the system. It was discussed by Einstein, Podolsky and Rosen in 1935 in the context of the interpretation of quantum mechanics: the famous "EPR paradox", which has since been extensively investigated theoretically and experimentally [see for example Rowe *et al.* Nature 409 791 (2001)].

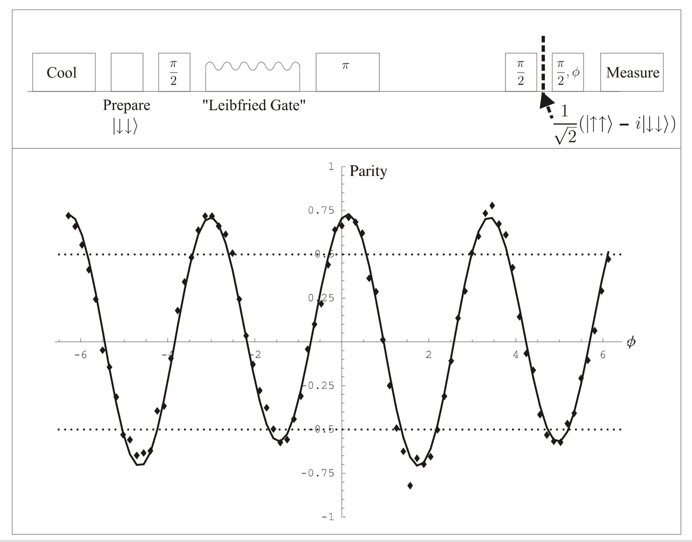
Entanglement is a key component of quantum computation; indeed, a quantum computer functions by controlled large-scale entanglement between its many qubits. In contrast to most of the systems used for studies of the EPR paradox, quantum computing requires *deterministic* entanglement, that is, production of entanglement on demand.

We demonstrate deterministic entanglement of two trapped-ion spin-qubits, using the method proposed and first demonstrated by Leibfried *et al.* [Nature 422 412 (2003)].

Entangling phase gate mechanism

- gate based on same oscillating spin-dependent driving force as used to create (single-ion) Schrödinger cat states
- ion-ion separation = integral number of standing wave periods
- ↑↑ ions or ↓↓ : same force on each ion (drives COM motion)
- ↑↓ ions or ↓↑ : opposing forces (drives stretch motion)
- driving force tuned close to stretch mode (resonant enhancement)
- if driven for correct time, ↑↓ and ↓↑ states acquire a phase of π/2





Results

- use spin-echo sequence to detect effect of phase gate, and reduce effect of magnetic field fluctuations
- at end of spin-echo, the entangled state (|↑↑⟩ − i|↓↓⟩) is produced
- a further π/2 analysis pulse with variable phase φ demonstrates cos(2φ) oscillations in the parity signal with amplitude >0.5
- parity amplitude implies entangled state produced with 75(5)% fidelity