Deterministic Entanglement of Trapped-Ion Spin-Qubits

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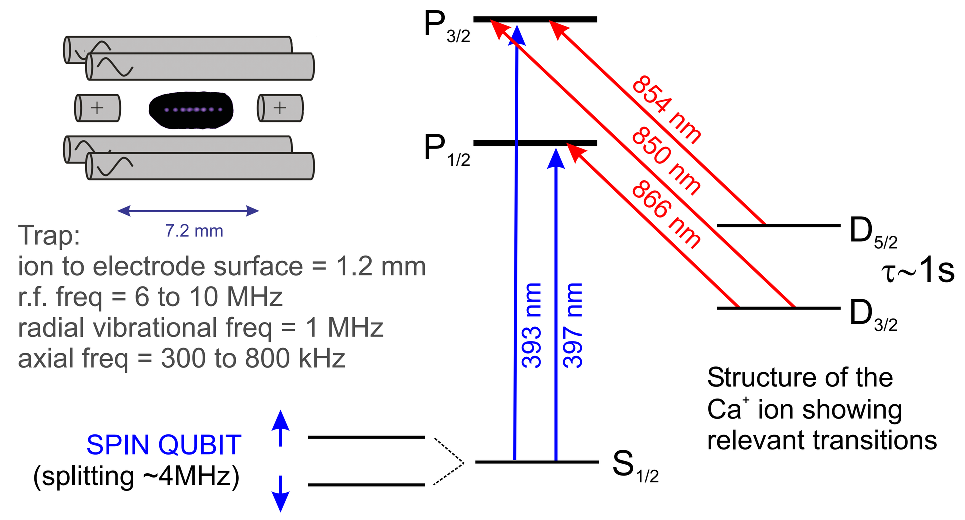
Main points

We present experiments and theory in quantum information processing using trapped ions.
This poster concentrates on entanglement and gates: see accompanying poster for cooling, coherence.



Summary of Results

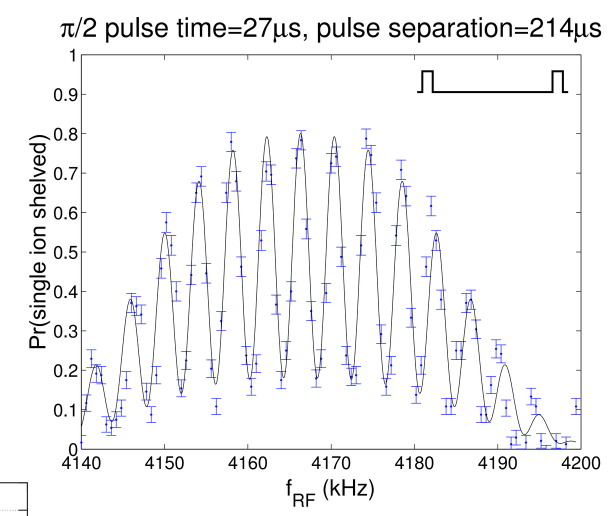
- 10 two-ion (2 qubit) Rabi flops with high visibility
- Deterministic entanglement of 2 ions (calcium 40 spin qubits) at 82(2)% fidelity
- Schrodinger cat with 1 ion and motion:
  - α up to 3.5(3) ($\langle n \rangle$=12)
  - well outside Lamb-Dicke regime: $\eta^2 2n$ = 1.6
  - α = 1 preserved for 422 µs with 80(20)% fidelity
  - also α = -2,0,+2 with 2 ions
- robust convenient tomography method
- (th.) factorization of general phase gates (ask for details)
- (th.) composite pulses for fast gate (t=1/trap freq) insensitive to optical phase

Single-qubit gates, 1-2 ions

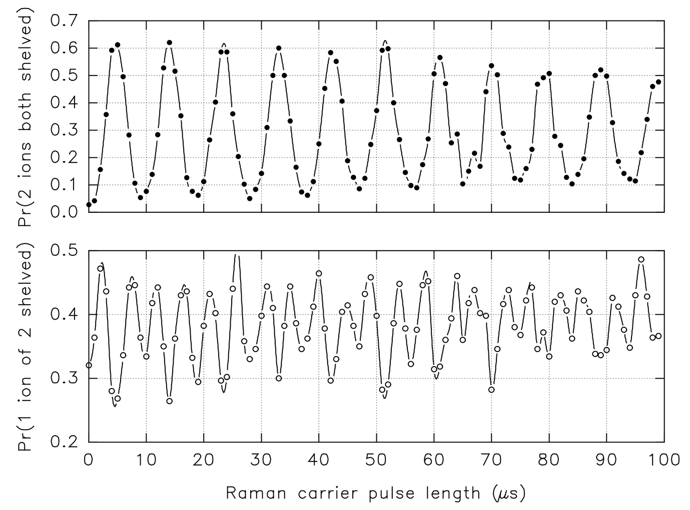
Spin qubit state coherently manipulated either by magnetic resonance or by stimulated Raman transition.

Single-ion Ramsey fringes

This data is for a two-pulse Ramsey sequence using magnetic resonance with a single trapped ion. Interference fringes are seen as the RF frequency is scanned.



Two-ion Rabi oscillations



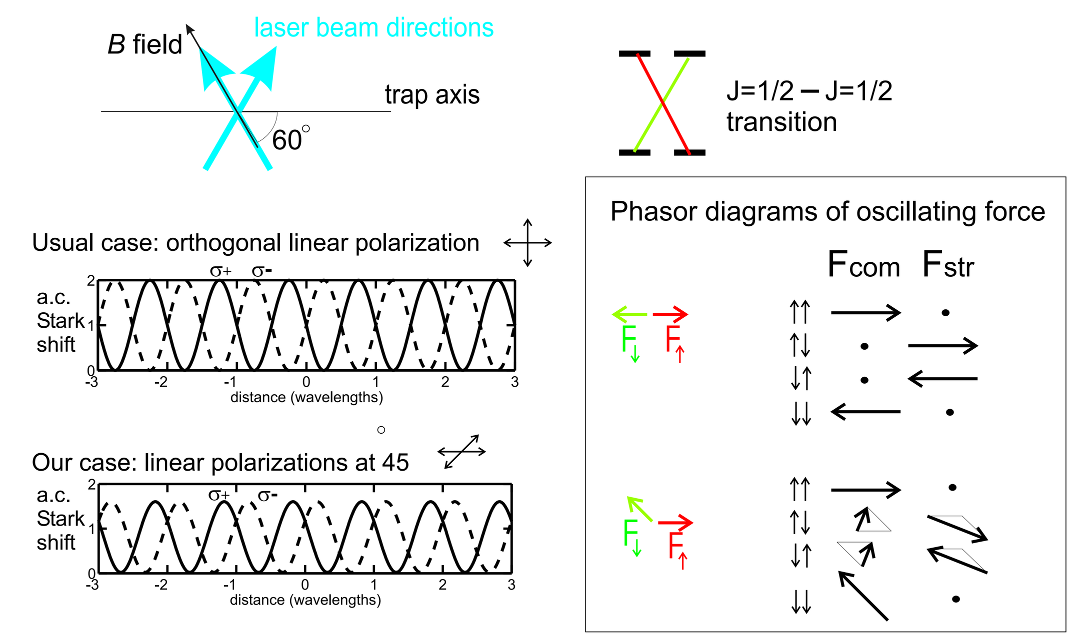
2-ion spin-state = 2 qubits. Rabi flopping, here driven by the Raman transition (4.5 µs π–time), gives a single-qubit rotation applied to both qubits simultaneously.

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

Coherence time (measured separately) of order 1 ms: the falling visibility here is a beating effect owing to unequal illumination of the ions.

Spin-dependent force

For two-qubit gates we use spin-dependent forces: push ions depending on spin state
→ Coulomb interaction gives a two-qubit phase.
The force is an optical dipole force in a standing wave with polarization gradient.

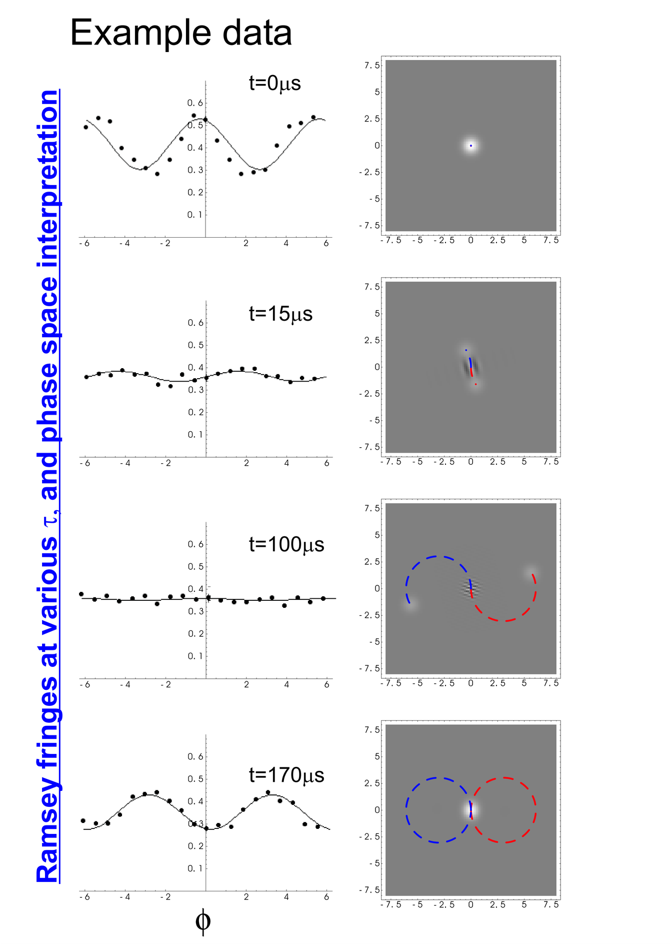


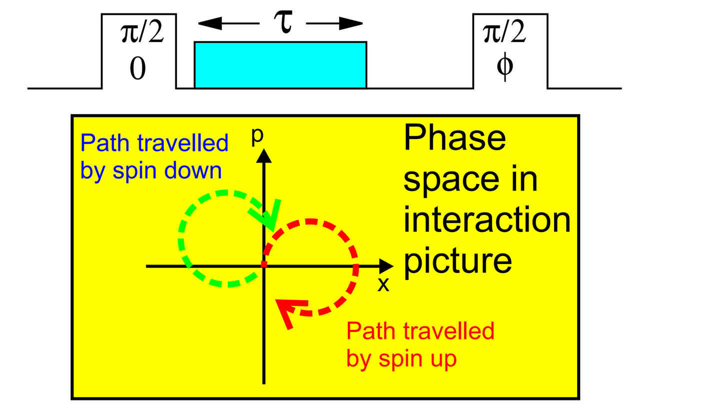
- A classical force displaces the motional state in phase space. e.g. oscillating force drives the state around a loop.
- Initial |n=0> displaced → Glauber coherent state
- When loop closes one has U=diag(exp(phases))
- **We have found a general mathematical method to decompose such U for multiple ions as a unique product of 1,2, ... n-qubit phase gates.**

Schrödinger Cat experiments

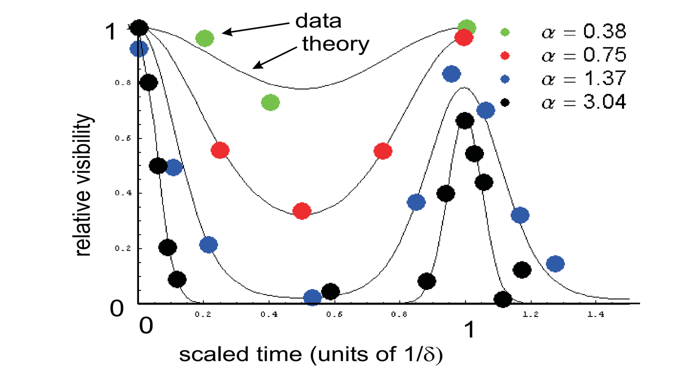
Coherent states of a harmonic oscillator approximate to classical motion, and a superposition of such states at mesoscopic excitation <n> is a type of Schrödinger cat.
Oscillating spin-dependent force → create such mesoscopic superpositions with single or pairs of ions. Spin state = measuring device 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).]

Example data

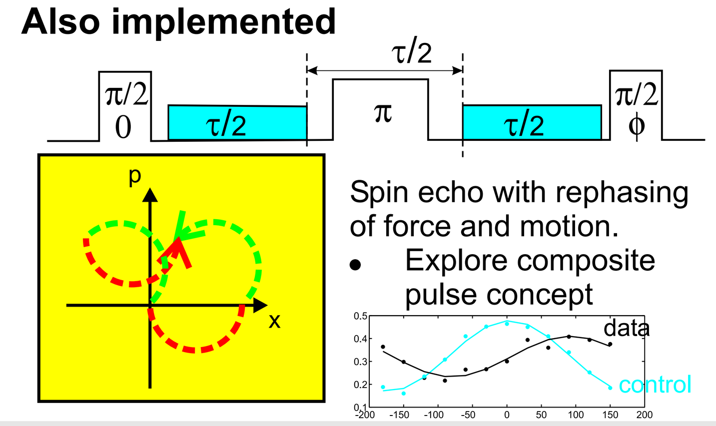




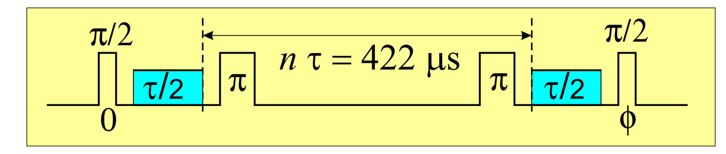
Visibility with increasing path size α



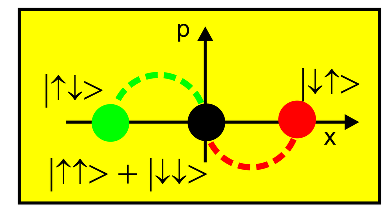
Also implemented



Spin echo with rephasing of force and motion.
- Explore composite pulse concept



Double echo: **long-lived cat:** τ_{coh} **> 2 ms**

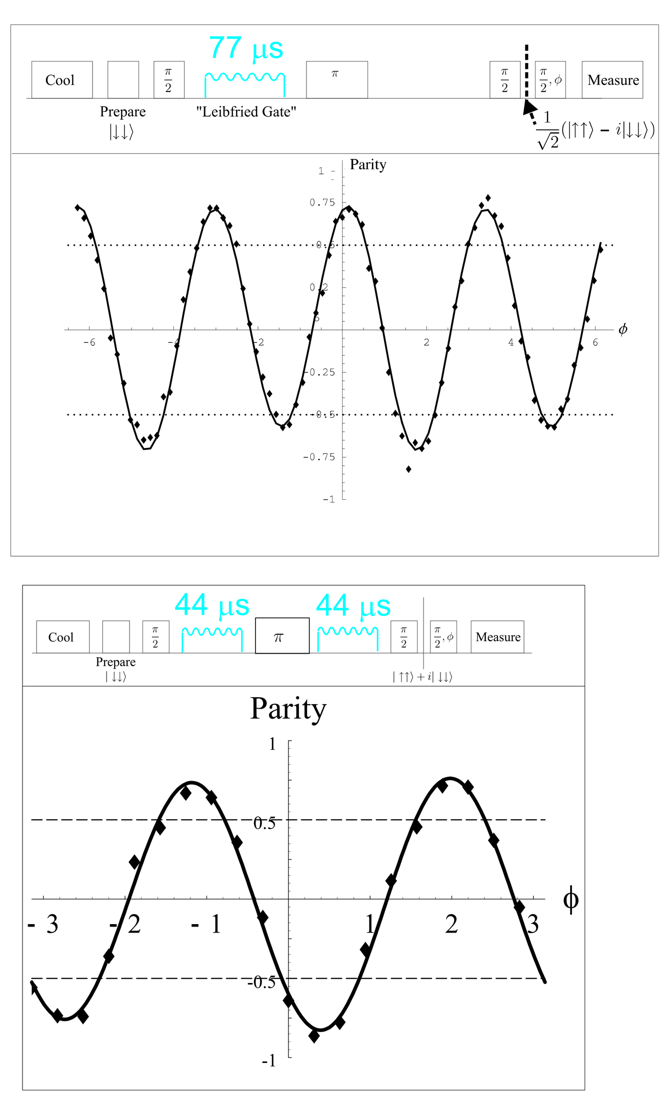


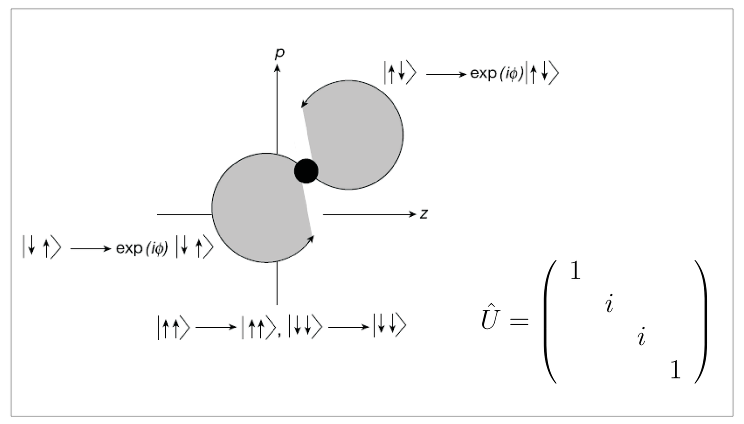
2 ions,
3 coherent states
α = -2, 0,+2

Deterministic entanglement

- Deterministic (i.e. single-shot, no post-selection) entanglement of 2 spin-qubits
- gate uses same oscillating spin-dependent driving force as to create Schrödinger cats, with force frequency close to ω_{str} & ion separation = integral number of standing wave periods

=> only stretch mode excited
=> states ↑↓, ↓↑ acquire a phase; ↑↑, ↓↓ do not. (Leibfried *et al.* [Nature 422 412 (2003)].)





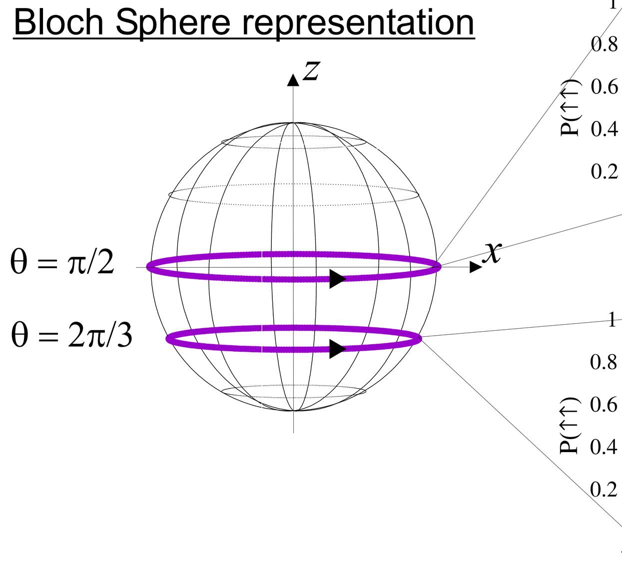
Results

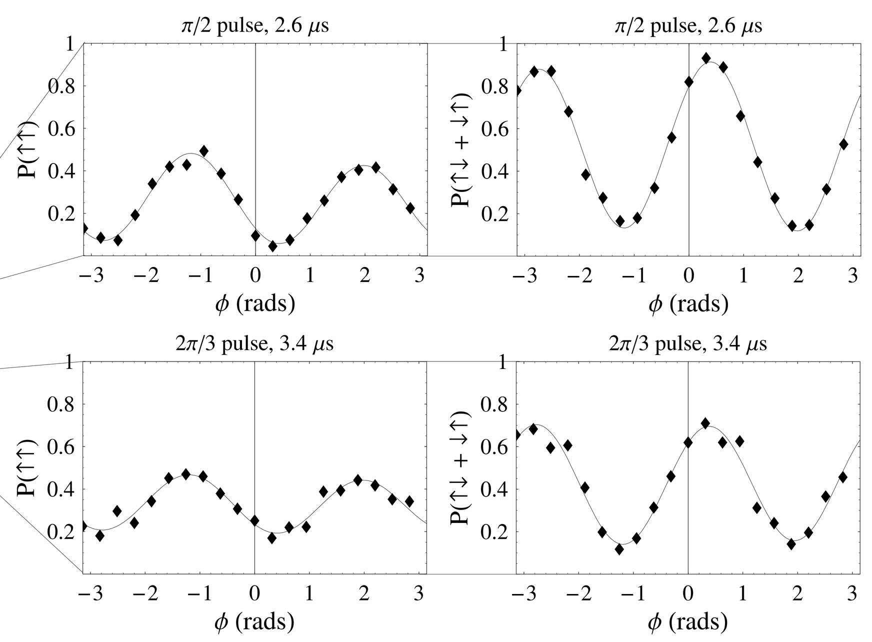
- Spin echo sequence to suppress slow drift effects
- ν_{com} = 500 kHz,
  ion sep = 9 µm = 22 λ
- the entangled state (↑↑ $-i$ ↓↓) is produced
- a further π/2 analysis pulse with variable phase ϕ demonstrates cos(2ϕ) oscillations in the parity signal with amplitude >0.5
- 1st exp: parity amplitude => entangled state fidelity > 75(5)%
- 2nd exp: two loops, one in each half of spin-echo: fidelity 82(2)%

Tomography

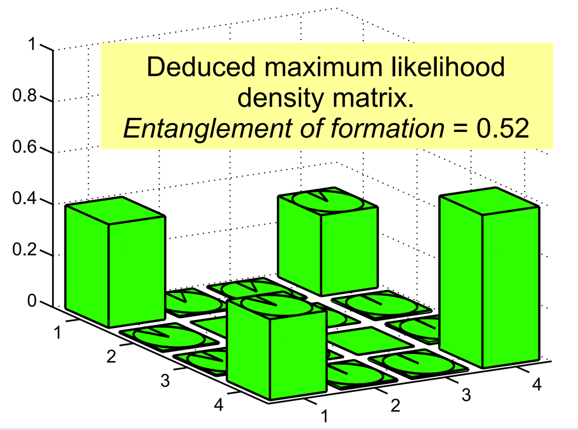
In general, tomography involves accumulating information by applying well-chosen rotations to the qubits and measuring them in a fixed basis. We developed a convenient scheme which is robust against typical experimental issues.
The rotation (same for all qubits) is through θ about an axis ϕ in the x-y plane. ϕ is scanned from -π to π: P(spin state) =Σ(sinusoidal functions of ϕ): this allows robust curve-fitting of sin functions with period π and 2π and an offset. Each contribution to the fit yields 1 or 2 real numbers; two values of θ are needed for complete information. A maximum likelihood estimation method is then used to obtain the physical density matrix closest to that obtained from the data.

Bloch Sphere representation





We show the results of tomography experiments on an entangled state $|\uparrow\uparrow\rangle + e^{i\varphi}\,|\downarrow\downarrow\rangle$.
The large amplitude of the oscillations with period π compared to those with period 2π indicate that the coherence between ↑↑ and ↓↓ is large.
(Our measurement method does not distinguish ↑↓ from ↓↑, but this has little influence for this example).



Composite pulses for fast robust gates

Wobble gate works well at low $\delta = \omega - \omega_{str}$ but is slow, $\tau = 2\,\pi\,/\,\delta$.
At high δ both COM and STR modes excited, can't close both loops in a single pulse (incommensurate freq).
Tailor f(t) in order to go faster? : lose insensitivity to optical phase φ_0.
- We find fast composite pulse sequences maintaining insensitivity to φ_0
- Issues: loop closure, constant area, lightshift phase

$$f(t) = \sum_{n=1}^{N} T\left((t-t_n)/\tau_n\right) f_n \sin(\omega_n t + \phi_n).$$

top hat

$$\phi_n = \phi_0 + \Delta\phi_n$$

random, fixed

$$\alpha(t) - \alpha(0) = \frac{i}{m\omega_0 a}\int_0^t e^{i\omega_0 t} f(t)\,dt.$$