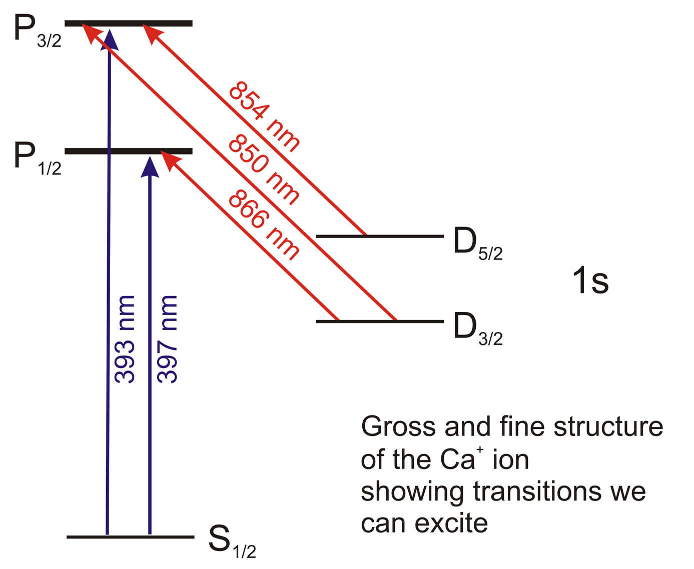
# Trapped calcium ions for quantum information experiments

J.P.Home, B.C.Keitch, D.M.Lucas, M.J.McDonnell, S.Nakayama, A.Ramos, M.Sasura, J.-P.Stacey, S.C.Webster, D.N.Stacey and A.M.Steane
*Centre for Quantum Computation, Clarendon Laboratory, Oxford University, U.K.*

Research supported by:
E.U. (QGATES/QUEST/CONQUEST)
ARDA (P-43513-PH-QCO-02107-1)
EPSRC
Royal Society

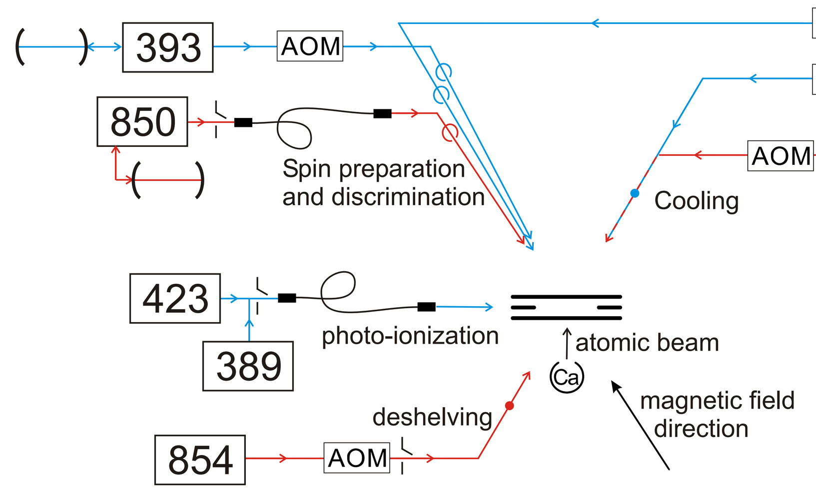
## Main points

- We are working with calcium ions held in a linear Paul trap.
- We present an angular momentum state measurement which can discriminate 1ħ in a single shot, even at zero magnetic field.
- We have selectively loaded all the stable isotopes of calcium by photo-ionization and measured a photo-ionization cross-section. We have trapped and cooled pure crystals of $^{43}Ca^+$.
- We observe  1ms coherence time of our spin qubit state by Rabi flopping using magnetic resonance.
- We have implemented continuous Raman sideband cooling close to the ground state, i.e. <n> < 1.
- Theoretical study of logic gate by selective ion displacement.



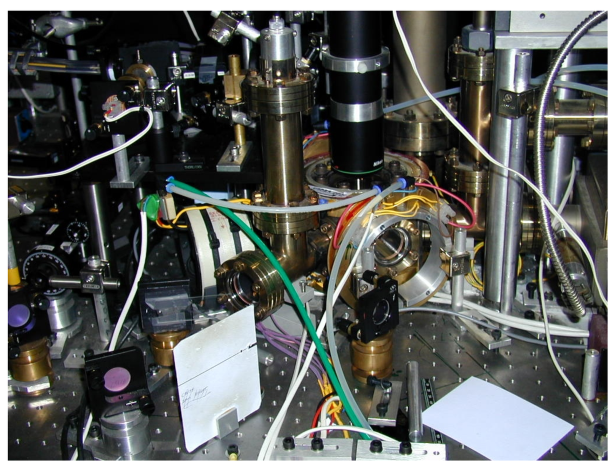

Gross and fine structure of the $Ca^+$ ion showing transitions we can excite

## Experimental details

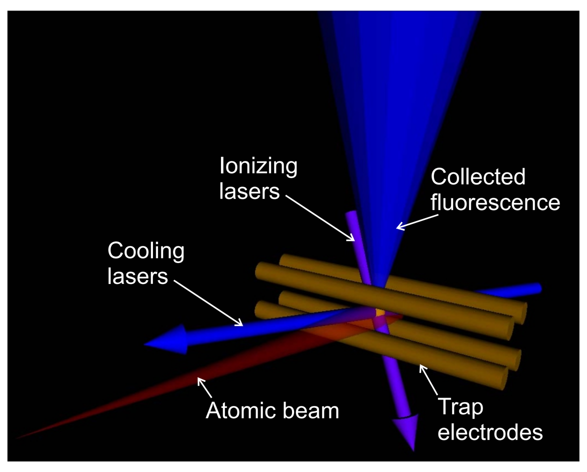



$_{rf}$=6.2MHz
$_z$=170-850 kHz
$_r$=500-1000kHz

All lasers are grating stabilized diode lasers, except the 389 which is a free-running diode.



View of vacuum system and collection optics

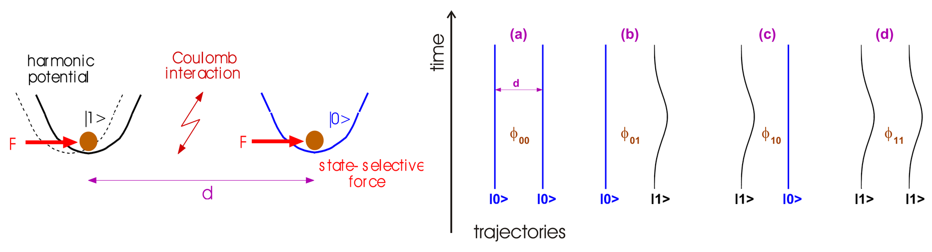



Geometry of photo-ionization system

## Theoretical study of quantum logic gate

### Fast Quantum Gates with Hot Trapped Ions

*Phys. Rev. A***67***, 062318 (2003), quant-ph/0402054*




A focused laser beam gives state-dependent push; Coulomb repulsion energy then results in a state-dependent phase (Cirac & Zoller, Nature 2000)

| | F | | S | |
|---|---|---|---|---|
| \|00> | | exp(i $_{00}$) \|00> | | \|00> |
| \|01> | | exp(i $_{01}$) \|01> | | \|01> |
| \|10> | | exp(i $_{10}$) \|10> | | \|10> |
| \|11> | | exp(i $_{11}$) \|11> | | exp(i )\|11> |

F=Pushing force, S=Single-qubit rotations

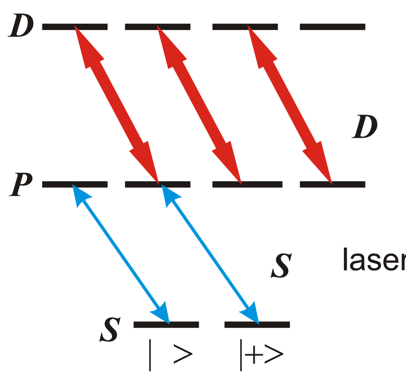
This is the 'controlled -phase' gate (equivalent to controlled-NOT).

*Issues*: photon scattering, intensity noise, thermal motion in non-uniform force

- PUSHING FORCE = Dipole optical force
- SPEED OF THE GATE  Typically $T_{gate}$~ 1 - 10  s
- ROBUST GATE  Laser cooling outside the Lamb-Dicke regime can be sufficient
- FIDELITY OF THE GATE  F ~ 0.9995 for ion separation d~30  m, trapping frequency  /2  ~310kHz and <n>~4
- FIDELITY LIMITED mainly by laser intensity fluctuations (can be reduced by balancing the gradient of the light shift with its size)
- REALISATION IN A LINEAR TRAP  Original method for 2-qubit gate with ions in separate traps can be extended to the case with 2 ions in the same trap
- TOFFOLI GATE (3-qubit CNOT gate) can be implemented!

## Detecting 1ħ of angular momentum

- Method to detect the angular momentum state of an atom, without the need for magnetic effects  e.g. it works at zero gyromagnetic ratio and/or zero field.
- Of fundamental interest, and also practically useful since insensitive to line-broadening (natural and laser linewidth) effects.

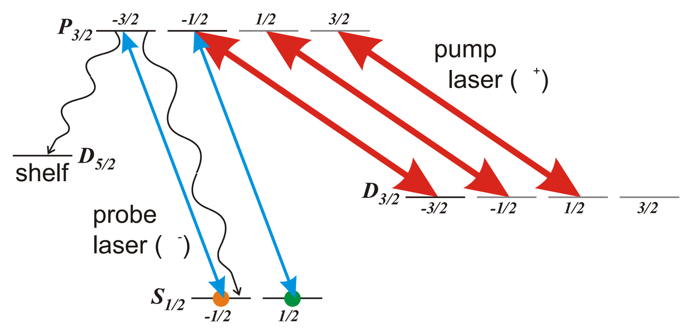


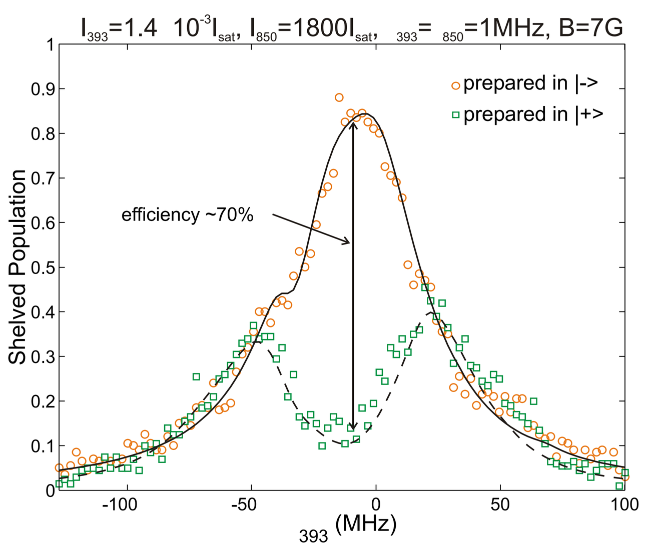

$$\frac{R_-}{R+} = \frac{3\Omega_D^2\Gamma}{(\Gamma^2+6\Omega_S^2)\gamma} \simeq \frac{3\Omega_D^2}{\Gamma\gamma} \gg 1$$

Principle:

- Pump laser strongly couples P(M=-1/2) and D(M=-3/2) but not P(M=-3/2) owing to angular momentum selection rules.
- Probe laser weakly drives fluorescence cycles for initial state |->, and optical pumping from |+> to |-> is prevented by EIT.
- There is no way to achieve this (i.e. many fluorescence cycles without optical pumping) using only single-photon processes.

Implementation in Ca: excitation causes optical pumping to metastable "shelf" $D_{5/2}$: easy to detect.

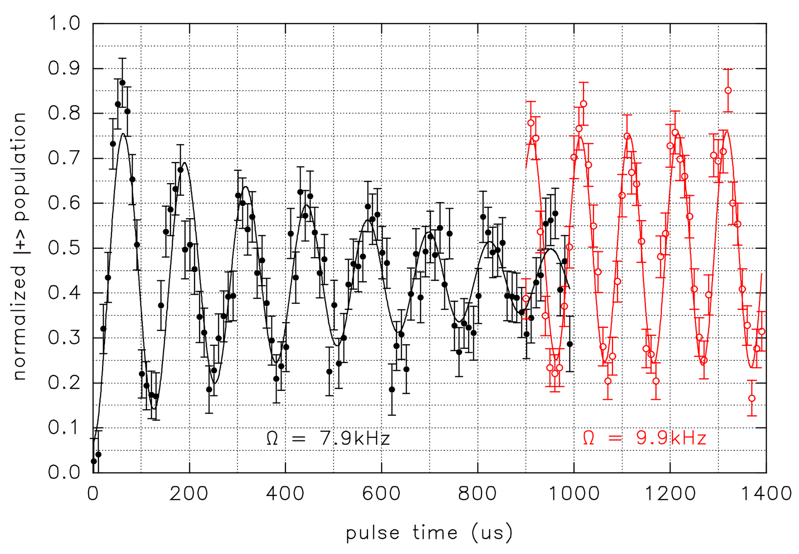



Dip shows suppression of excitation by EIT (unwanted excitation suppressed by factor ~ 200; the shelving branching ratio = 5% to give observed ratio shelving/spin relaxation rate ~10).

## Magnetic resonance Rabi oscillations

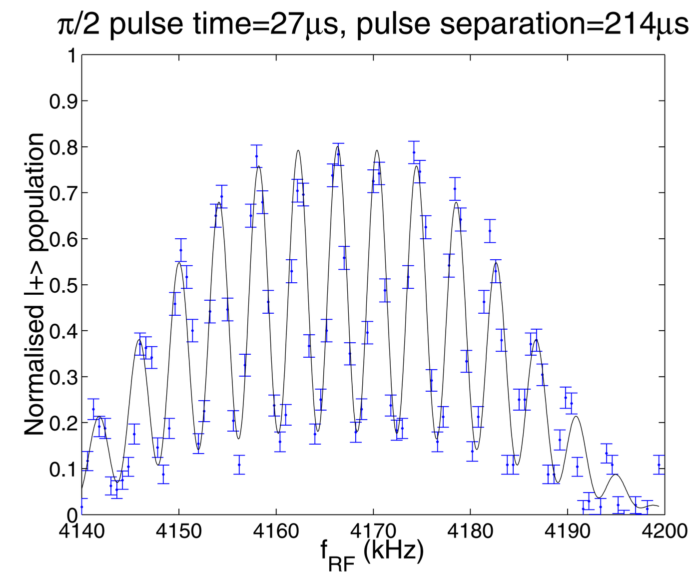
Using an oscillating magnetic field tuned to the ground state Zeeman energy separation (4MHz) we are able to coherently manipulate the two magnetic substates




Rabi oscillations as a function of pulse length:

- Magnetic field noise leads to decoherence time ~ 500  s (black curve).
- With 50Hz a.c. line trigger, decoherence time ~ 1.2ms (red curve).

$\pi/2$ pulse time=27$\mu$s, pulse separation=214$\mu$s




Ramsey fringes as a function of oscillating magnetic field frequency.

Future work:

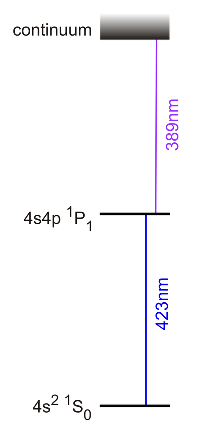
- Investigate sources of decoherence
- Use a light shift to produce a 1-qubit phase gate
- Apply "pushing gate" method to entangle ion qubits

## Photo-ionization loading

### Method

Two major advantages over electron bombardment:

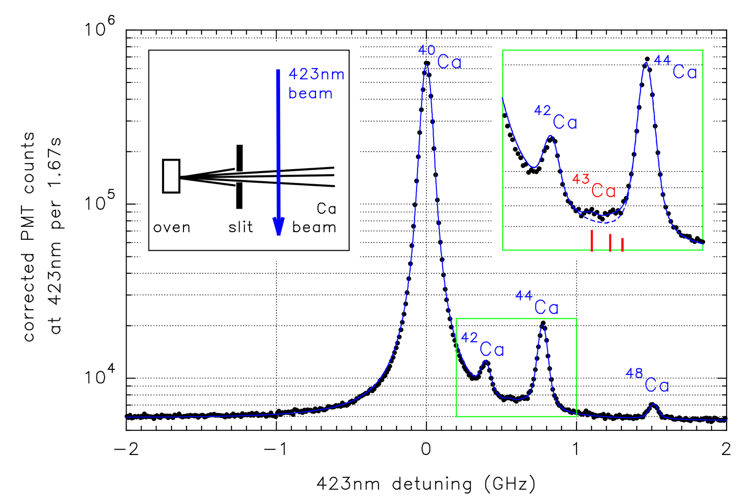
- The loading process is much less perturbative to the trapping environment.
- We can select which isotope we load into the trap.




Neutral calcium transitions used for photo-ionization [see also Gulde *et al.*, App.Phys.B**73** 861 (2001)]. The transition at 423nm is the isotope-selective excitation.

| Mass number | Natural abundance | Observed loading probability |
|---|---|---|
| 40 | 96.9% | ~100% |
| 42 | 0.647% | ~80% |
| 43 | 0.135% | ~50% |
| 44 | 2.09% | ~100% |
| 46 | 0.004% | ~10% |
| 48 | 0.187% | ~100% |

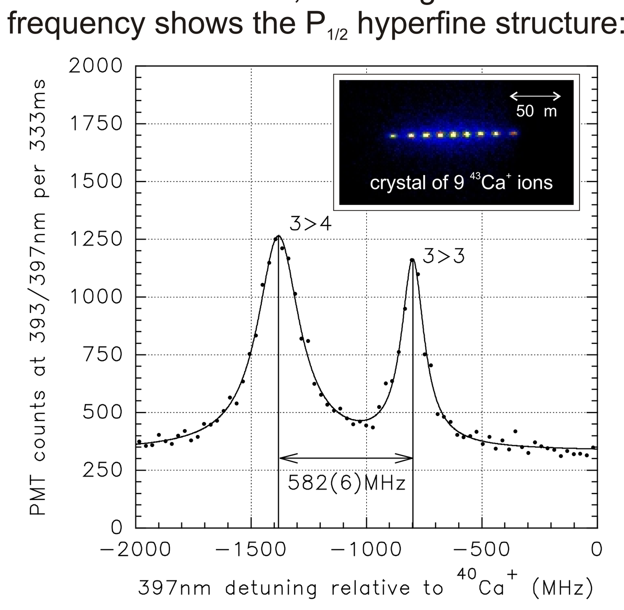
We deduce the cross-section for ionization by the 389nm laser to be 170(60) megabarns.




The graph shows the 423nm fluorescence scattered from the atomic beam as the 423nm laser frequency is scanned over the resonance of the various isotopes in the beam.

### Calcium-43

- We are able to load pure crystals of $^{43}Ca^+$ by combining photo-ionization with laser heating of other isotopes to expel them from the trap.
- We cool on the 393nm transition and repump on the 397nm transition; scanning the 397nm frequency shows the $P_{1/2}$ hyperfine structure:



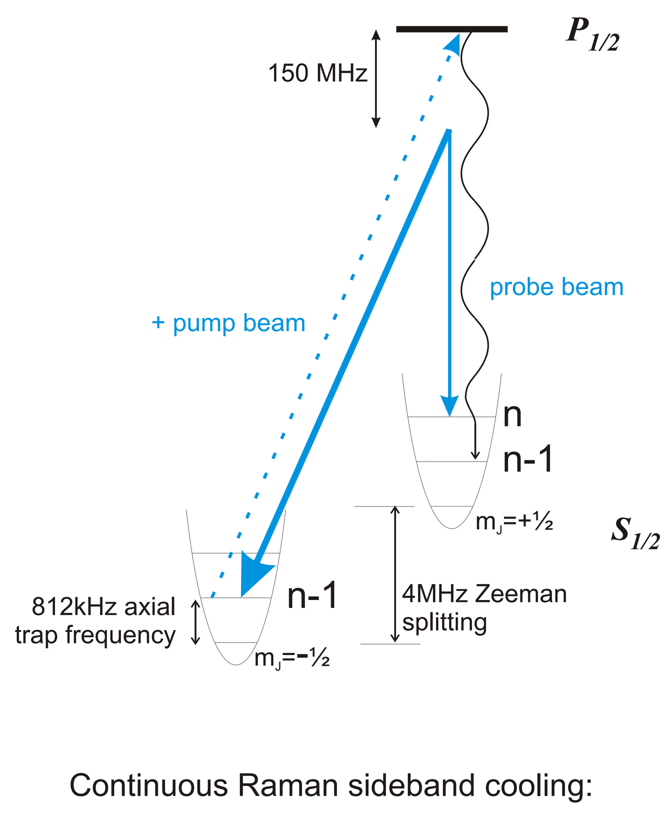

- Using an EOM to add sidebands at 3.2GHz to the 397nm laser, we can Doppler-cool without a separate u.v. repumping laser.

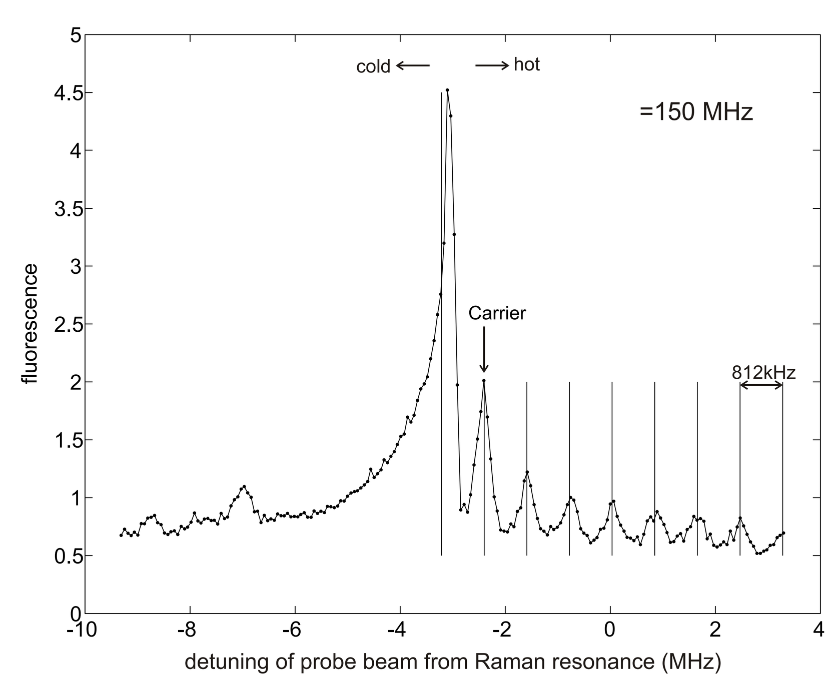
Future:

- Use the hyperfine structure as a qubit.
- Magnetic-field insensitive states exist.
- Large fine structure splitting ⊳ good-fidelity gates based on Raman transitions possible.

[See: Lucas *et al.*, Phys. Rev. A**69** 012711 (2004).]

## Sideband Cooling




Continuous Raman sideband cooling:

- Raman beams move population from |+½,n> to |-½,n-1>.
- The intense  + beam optically pumps population in |-½,n-1> to |+½,n-1>.
- The net result is a loss of one vibrational quantum.

Fluorescence (a.u.) resulting from scanning the probe laser over the Raman resonance.

- Vertical lines separated by 812kHz show the axial trap sidebands.
- First red sideband provides the lowest ion temperature, <n> < 1. Probe detunings greater than this still result in a low ion temperature.
- Between the first red sideband and the carrier the Raman process stops cooling the ion. We still see fluorescence on the blue sidebands as the single photon repumping provides cooling.