Quantum Information and Neutral Atoms

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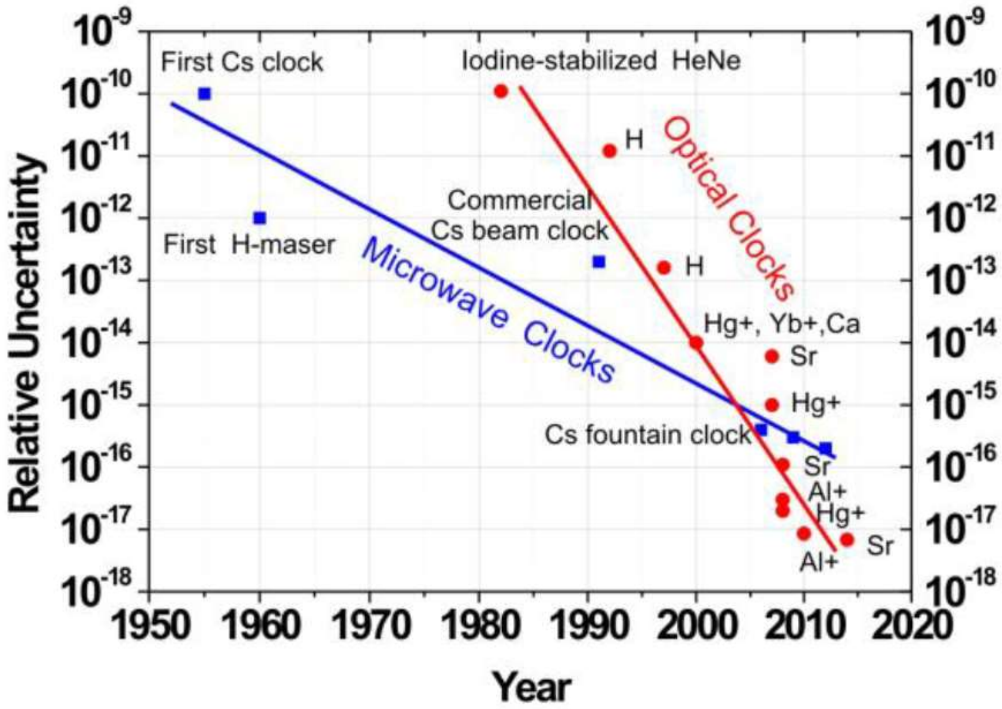
Advances in Quantum Technology with Neutral Atoms

- Clocks
- Interferometers
- Magnetometers

- Atomtronics
- Many Body Physics

- Hybrids

- Quantum Information



Zehuang Lu, “Optical atomic clock ”; to be published in Journal of Optics

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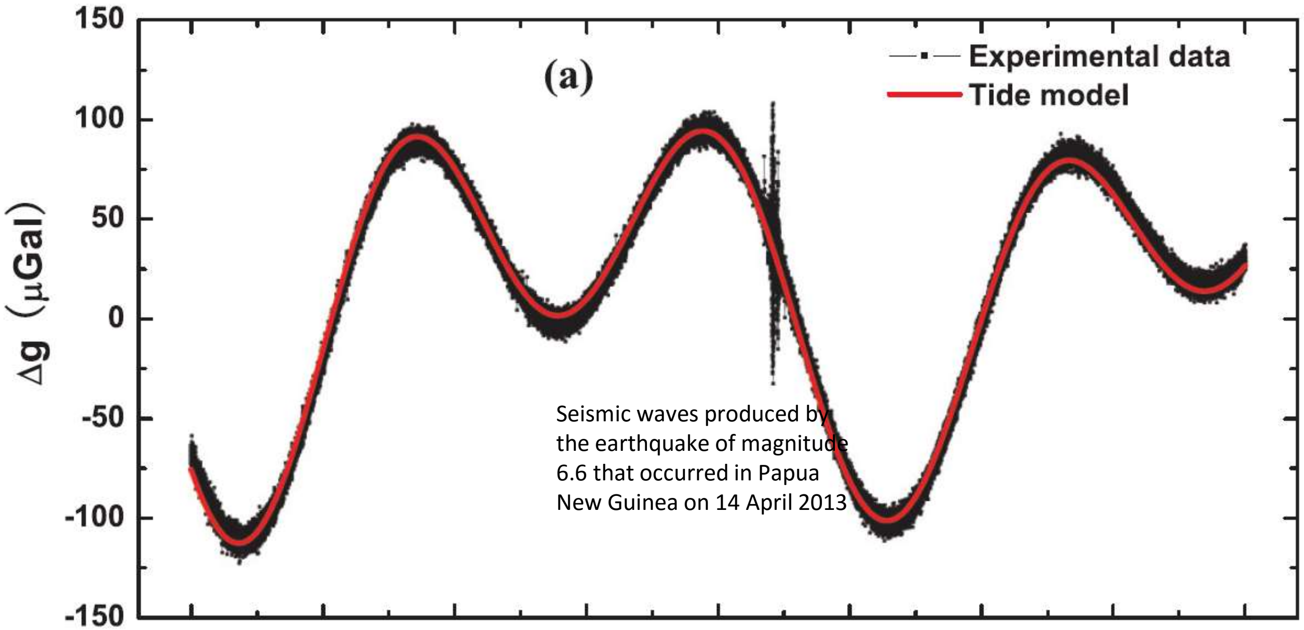

Zhong-Kun Hu, Bu-Liang Sun, Xiao-Chun Duan, Min-Kang Zhou, Le-Le Chen, Su Zhan, Qiao-Zhen Zhang, and Jun Luo, Phys. Rev. A;, 88, 043610 (2013)

Neutral Atoms

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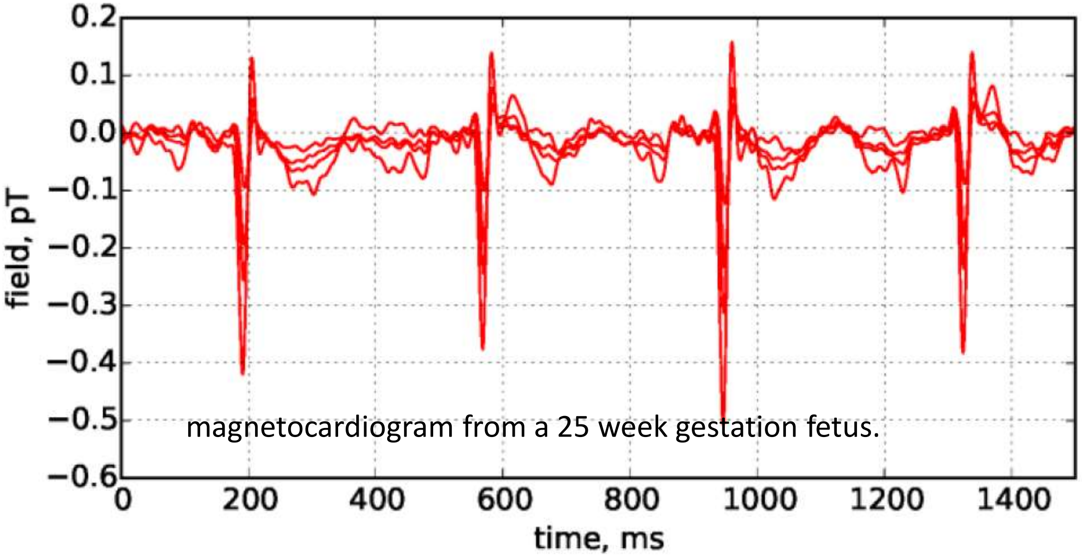

Antoine Wesis, “Optical magnetometers”; to be published in Journal of Optics

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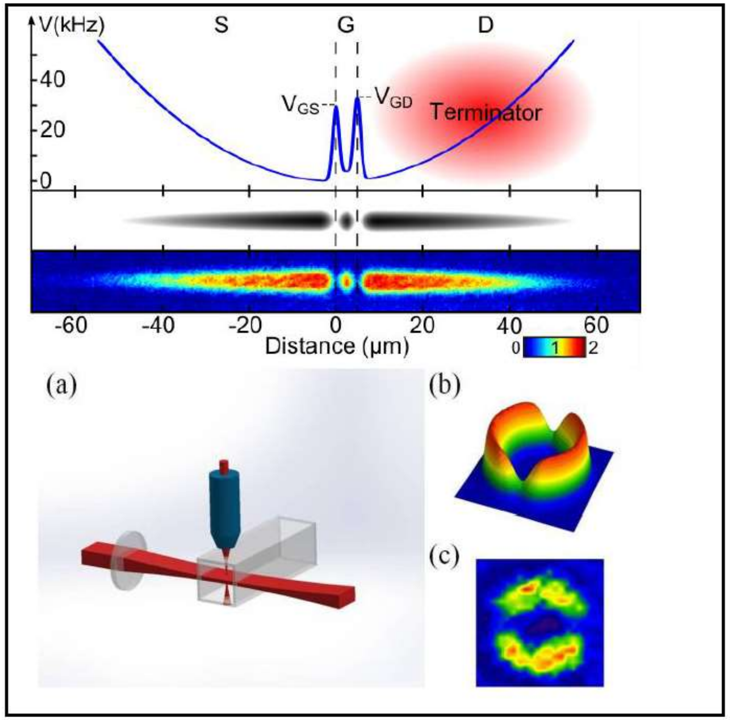

Luigi Amico, Malcolm G. Boshier; "Atomtronics"; to be published in Journal of Optics

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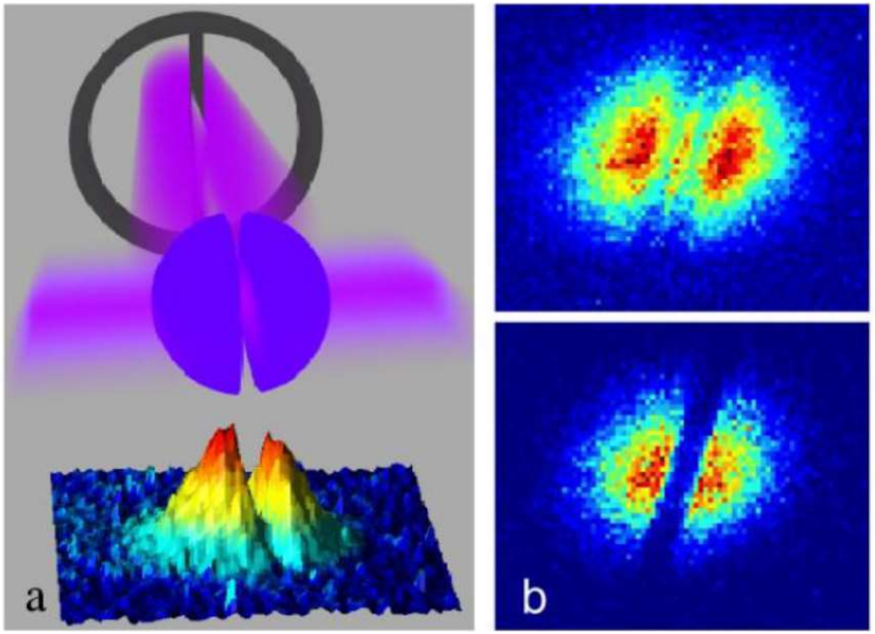

T.C. Kilian, “Stretching the boundaries of plasma physics with ultracold neutral plasmas”; to be published in Journal of Optics

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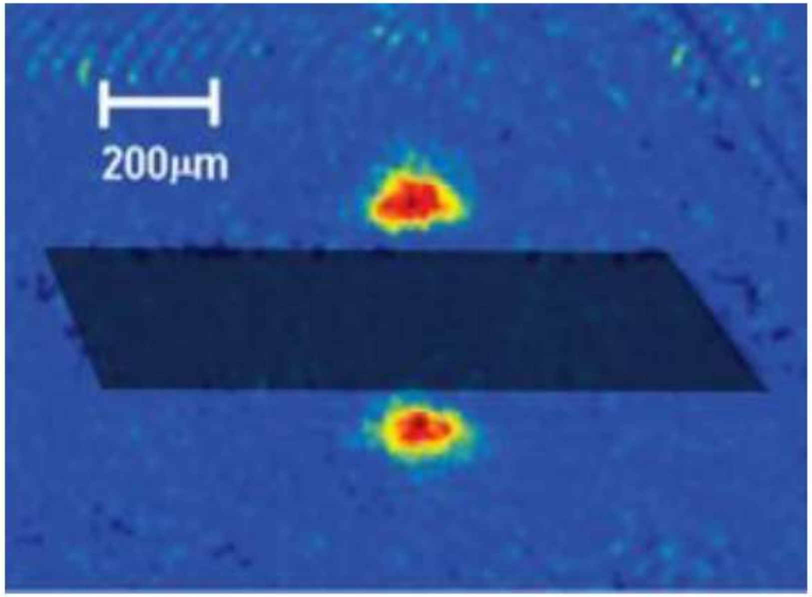


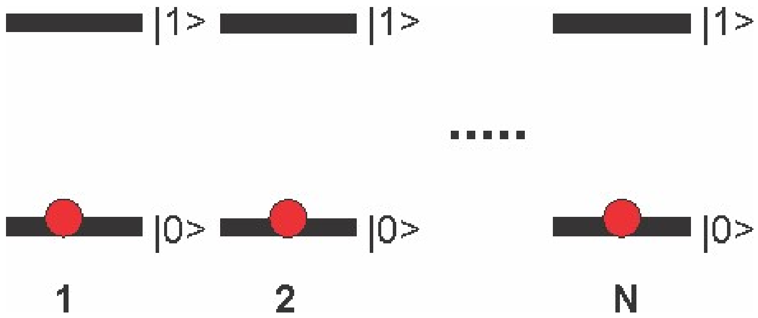
Ch. Hufnagel, R Dumke, “Superconducting atom chips and hybrid quantum systems”; to be published in Journal of Optics

The DiVincenzo Criteria

- A scalable physical system with well-characterized qubits.
- The ability to initialize the state of the qubits , for example|000..0>
- Long relevant decoherence times, much longer than the gate operation time.
- A “universal” set of quantum gates.
- A qubit-specific measurement capability.
- The ability to interconvert stationary and flying qubits.
- The ability to faithfully transmit flying qubits between specified locations.

David P. DiVincenzo “The Physical Implementation of Quantum Computation“, Fortschritte der Physik 48, 771 (2000).

The DiVincenzo Criteria



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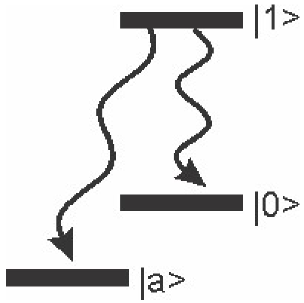

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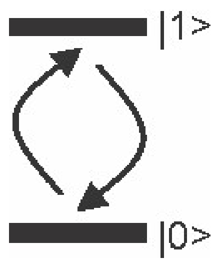

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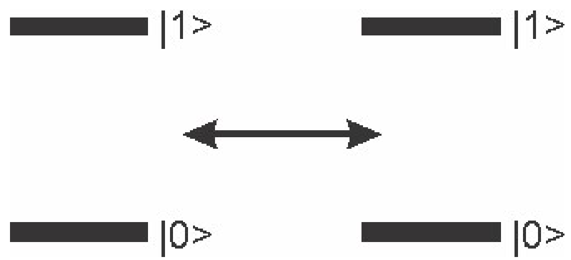

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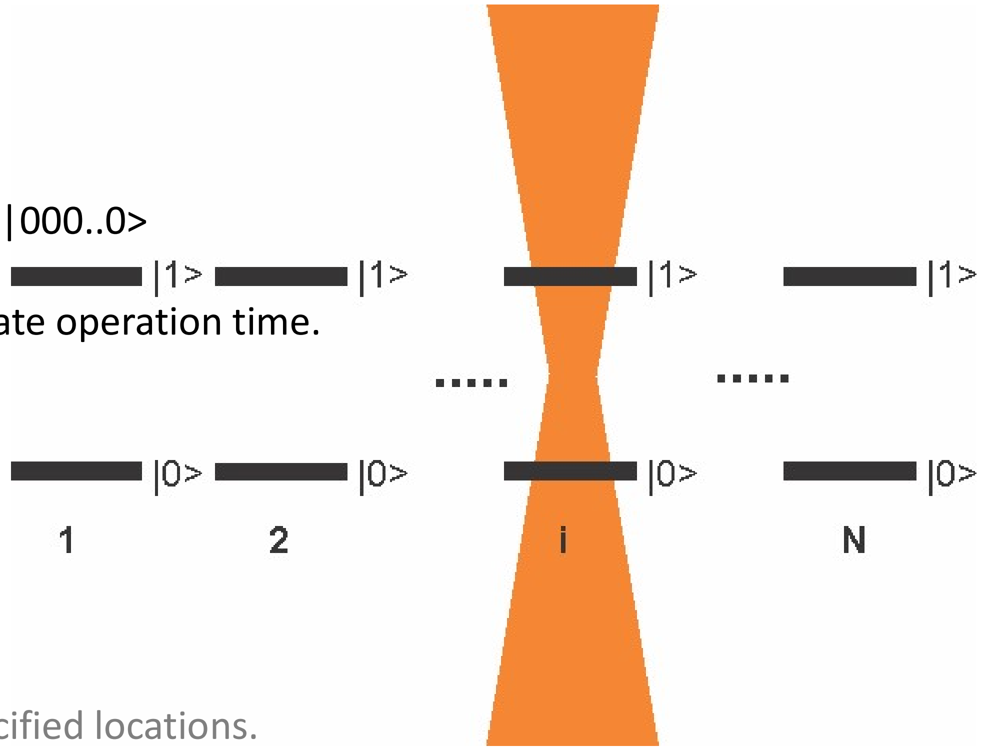

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Qubit Realization with Neutral Atoms

Traps for Neutral Atoms

Gates with Neutral Atoms

Architectures with Neutral Atoms

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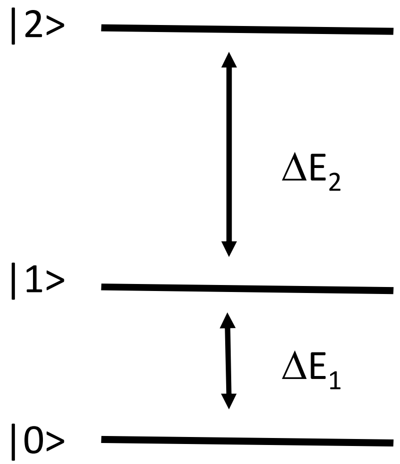
Desired Properties of Single Qubit

- Isolated two level scheme
  - $\Delta E_2 - \Delta E_1 >> \Gamma$
- Coupling to external fields for manipulation
  - Coupling to EM-field for initialization
- Isolation from environment
  - Insensitive to fluctuations of EM fields



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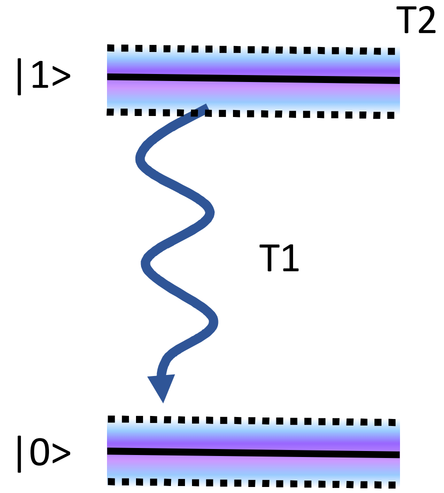
Decoherence Times

T1: measures the loss/change of energy from the system. Change of probability of occupation.

T2: Change of phase of qubit state (superposition)



$$|\psi> = \alpha|0> + \beta|1>$$

$$\rho = |\psi><\psi| = \begin{bmatrix} |\alpha|^2 & \alpha\beta^* \\ \beta\alpha^* & |\beta|^2 \end{bmatrix}$$

T1: change of amplitude $|\alpha|^2$ or $|\beta|^2$

T2: change of phase $\alpha\beta^*, \beta\alpha^*$ (loss of purity)

Experimental T2 < T1

Qubit Realization with Neutral Atoms

- Motional States
- Currents in a Ring Lattice
- Hyperfine Levels
- ....

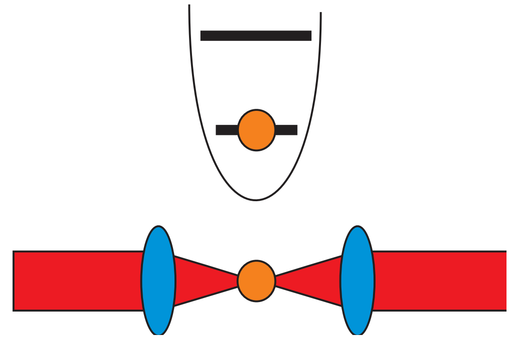
Motional Qubit States

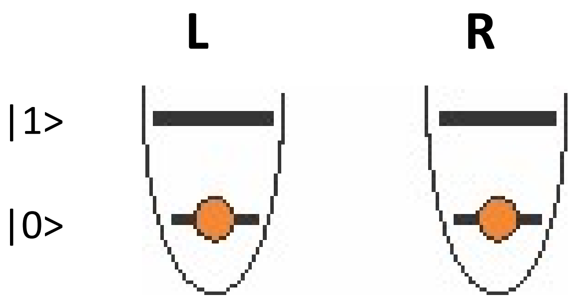
- Qubits can be encoded in the vibrational states of atoms in tight traps

- Computational Basis:

Vibrational ground state and first excited state
|0> and |1>

Occupation of Left and Right Potential
|L> and |R>





Eckert, K., Mompart, J., Yi, X.X., Schliemann, J., Bruß, D., Birkl, G., Lewenstein; M. Phys. Rev. A **66**(4), 042317 (2002)
Mompart, J., Eckert, K., Ertmer, W., Birkl, G., Lewenstein, M; Phys. Rev. Lett. **90**(14), 147901 (2003)

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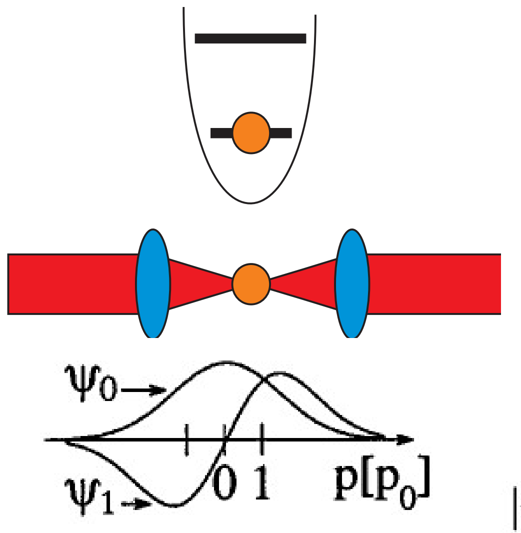
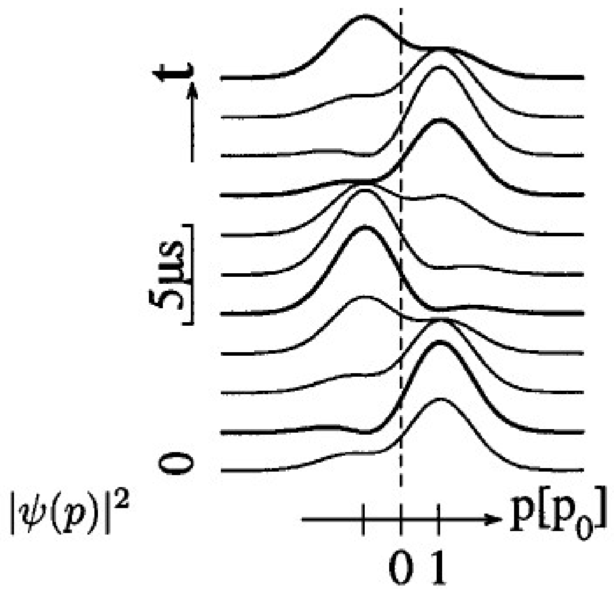
Motional Qubit States

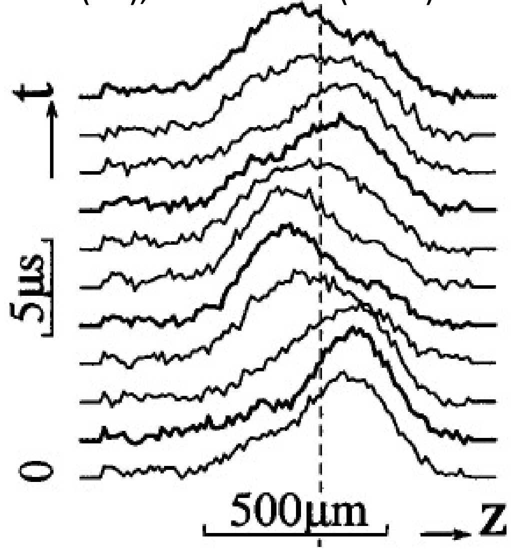
Morinaga, M., Bouchoule, I., Karam, J.C., Salomon, C.; Phys. Rev. Lett. **83**(20), 4037–4040 (1999)



Wave functions in momentum representation of the states |0> and |*n*>. The momentum unit is the rms ground state width *p*0



Calculated evolution of the momentum distribution in superposition



The measured time evolution of the velocity distribution of the superposition state. The time origin is the end of the Raman pulse.

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Qubits Neutral Atoms

Qubit Realization with Neutral Atoms

- Motional States
- Currents in a Ring Lattice
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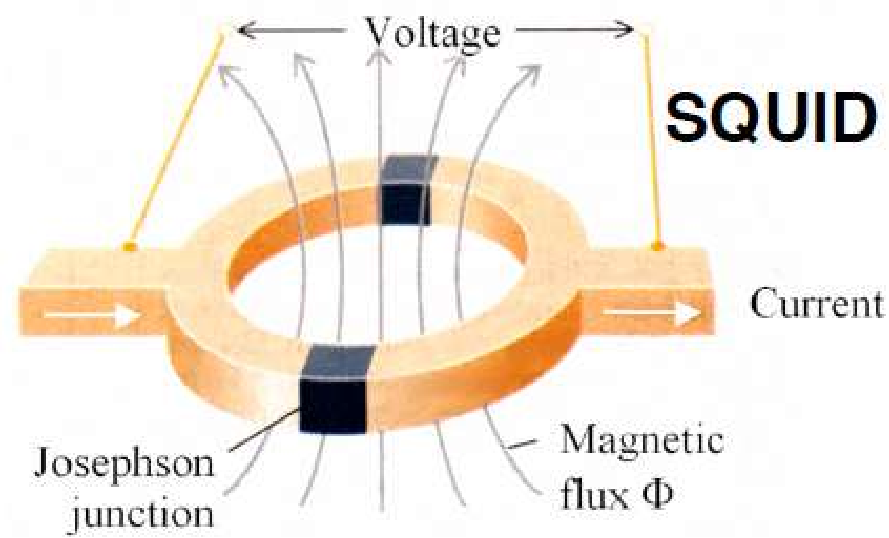
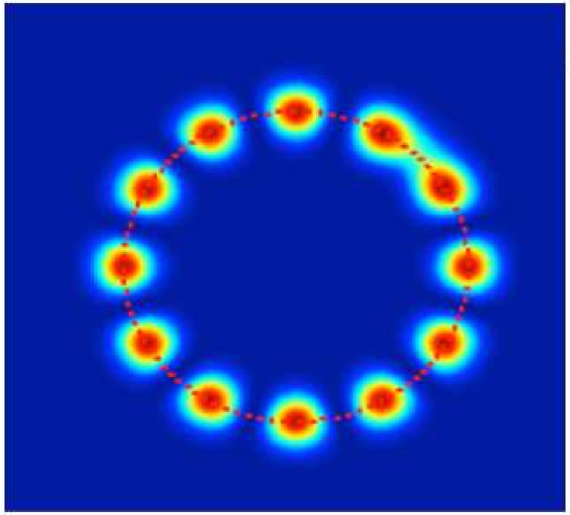
Current States

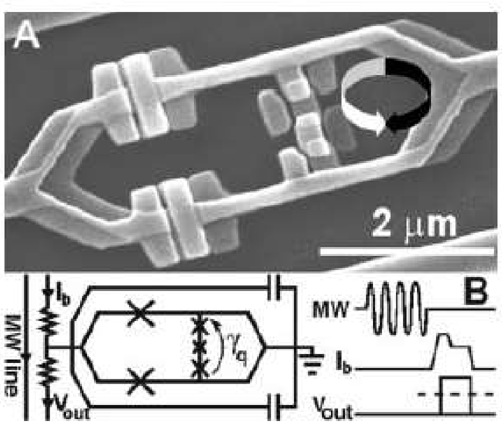


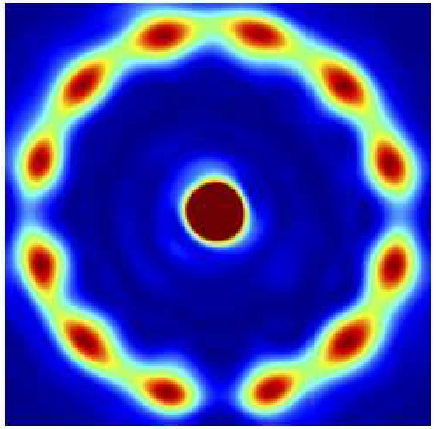


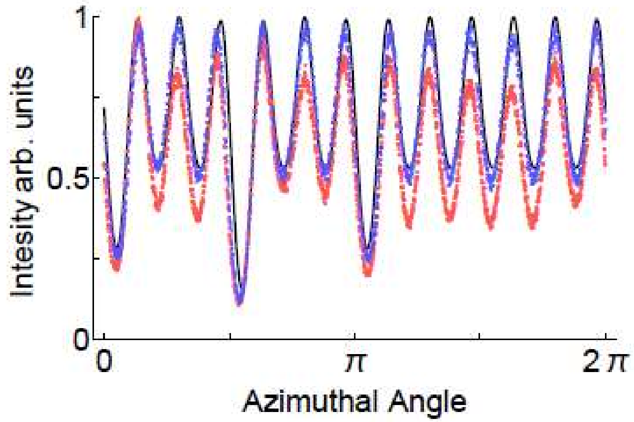
The Ring-Lattice system provides control with onsite interactions U, flow control via tunnelling t, weak link barrier control Λ, and system size M

L. Amico, D. Aghamalyan, F. Aksztol, H. Crepaz, R. Dumke & L. C. Kwek; Scientific Reports 4, 4298 (2014)

Current States





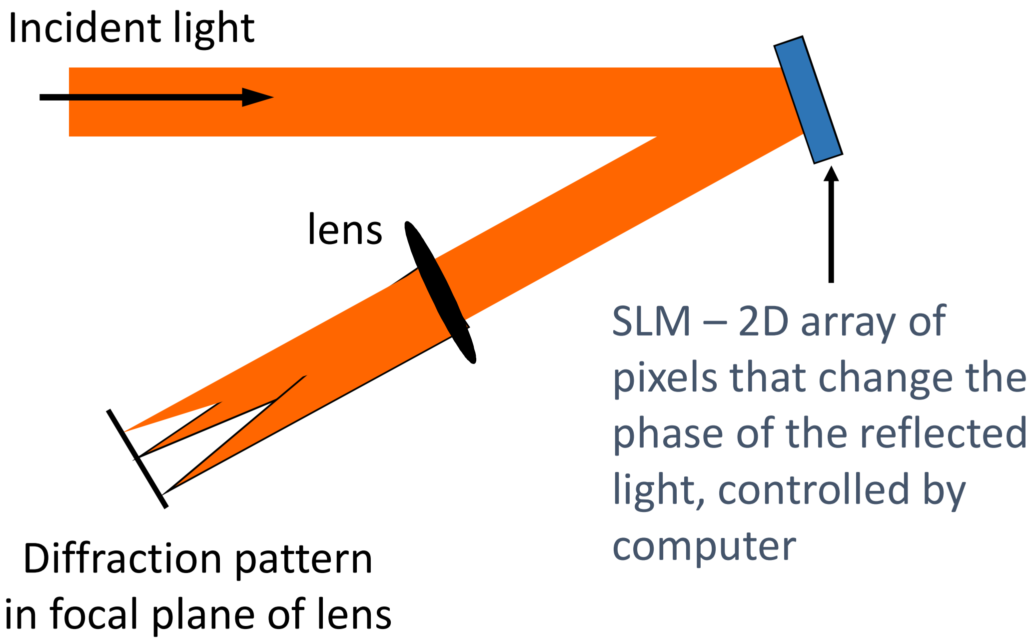


I. Chiorescu, P. Bertet, K. Semba, Y. Nakamura, C. J. P. M. Harmans and J. E. Mooij; Nature **431**, 159-162 (9 September 2004)

SLM

An electro-optical device which imposes some form of spatially varying modulation on a beam of light

LCOS (Liquid crystal on silicone) display head (Holoeye)



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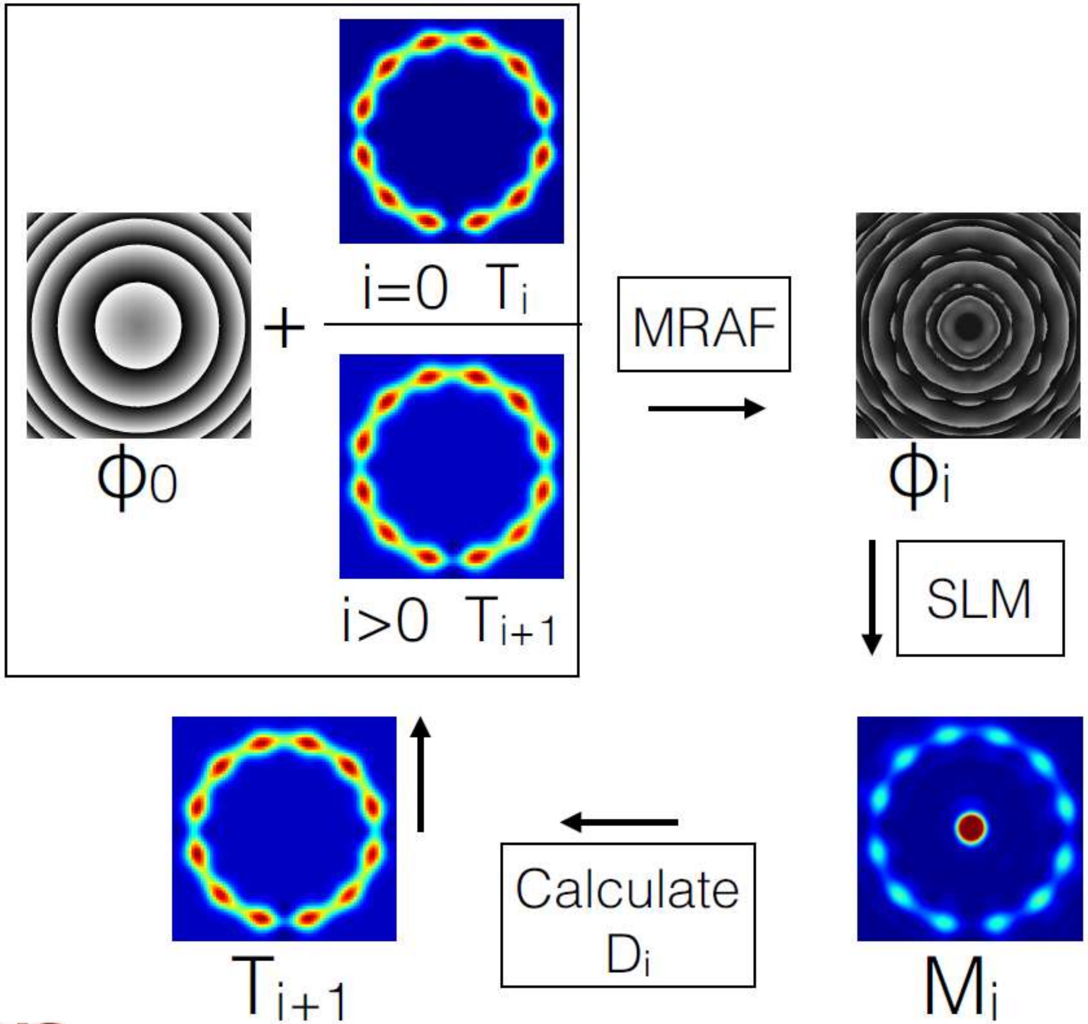

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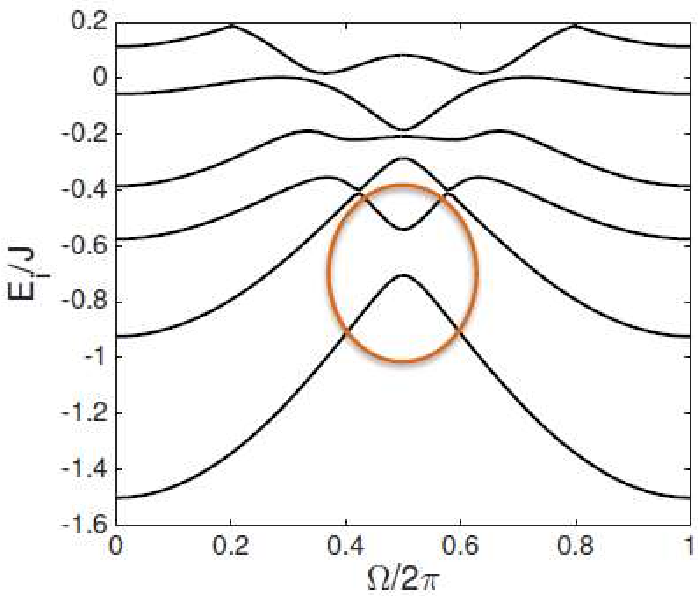

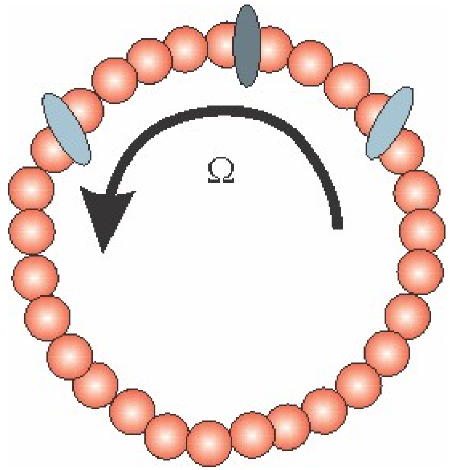

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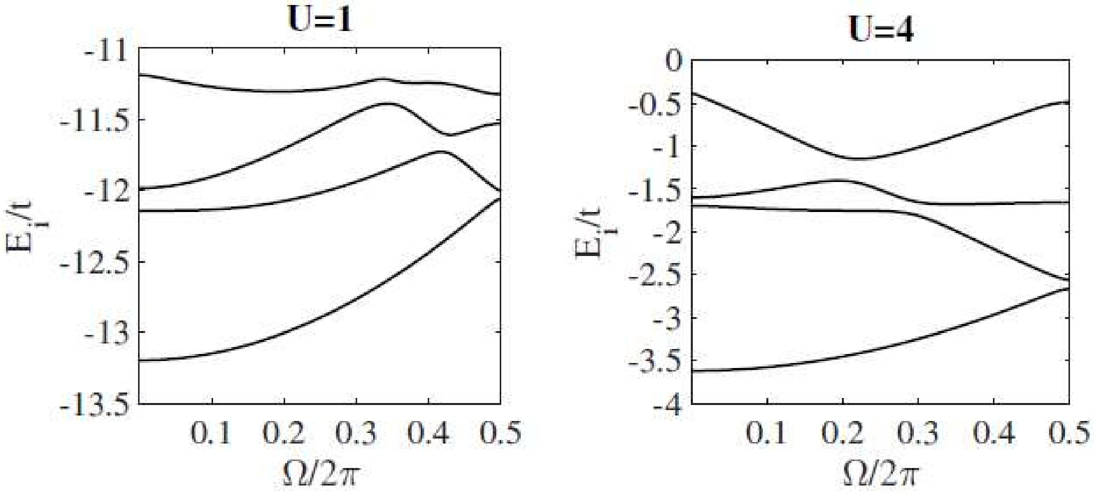

Here M=8 (number of sites), N=10 (number of particles), t'=0.5t and t''=0.8t (hoping parameter)

By adjusting the ratio of the weaklinks t'', t' and t we gain extra control over the system

D. Aghamalyan, N.T. Nguyen, F. Auksztol, K. S. Gan, M. Martinez Valado, P. C. Condylis, L.-C. Kwek, R. Dumke, and L. Amico; arXiv:1512.08376 [quant-ph]; 2015

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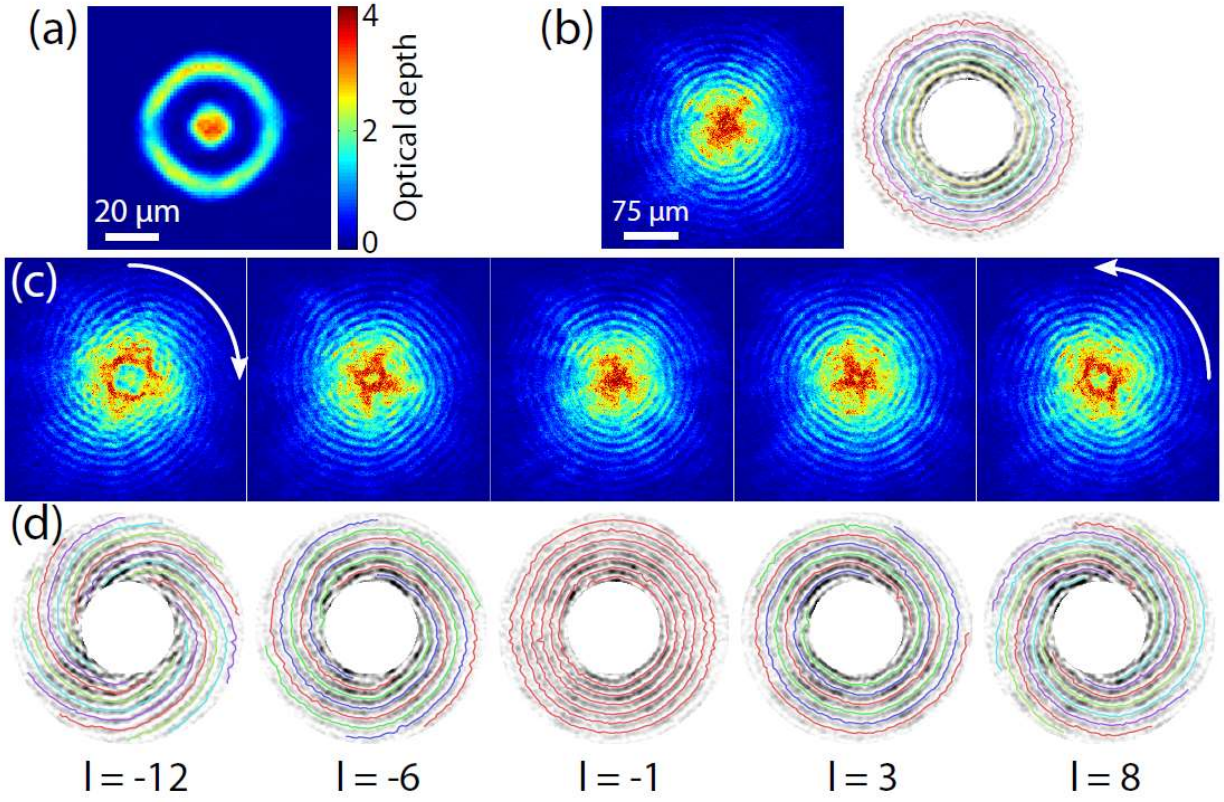

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S. Eckel, F. Jendrzejewski, A. Kumar, C. J. Lobb, and G. K. Campbell; Phys. Rev. X **4**, 031052,2014

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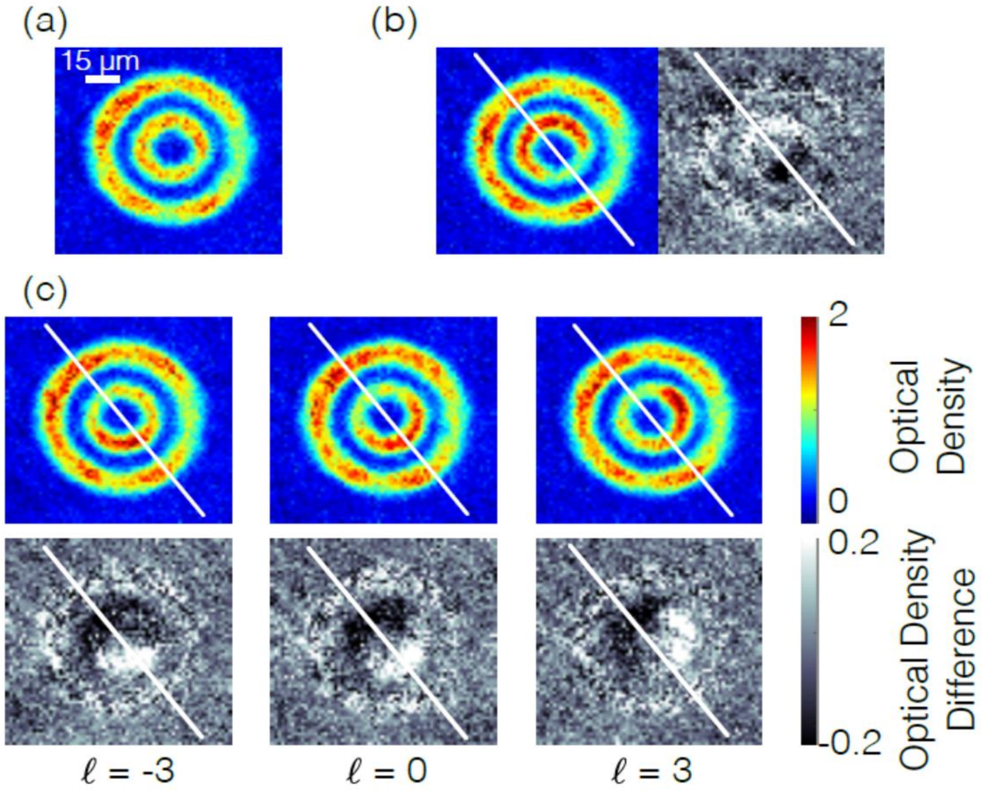

A. Kumar, N. Anderson, W.D. Phillips, S. Eckel, G.K. Campbell, S. Stringari; arXiv:1509.04759 [cond-mat.quant-gas] (2015)

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Qubit Realization with Neutral Atoms

- Motional States
- Currents in a Ring Lattice
- Hyperfine Levels
- ....

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Hyperfine States

-At the position of the nucleus, there is a magnetic field $\mathbf{B_J}$. (Similar to the finestructure coupling $\mathbf{B_L}$)

- This influences the magnetic moment of the nucleus and orients the nuclear spin.

- The result of this interaction is a coupling of the angular momenta of the electrons **J** and the nucleus **I** to a new total angular momentum **F**.

- Hyperfine: three orders of magnitude smaller than the fine structure energy. (Given by the ratio of the magnetic moments of nuclei and electrons.)

Hyperfine States

Total angular momentum:

(total angular momentum of the electron) **+** (angular momentum of the nucleus)

$$\boldsymbol{F} = \boldsymbol{J} + \boldsymbol{I}$$

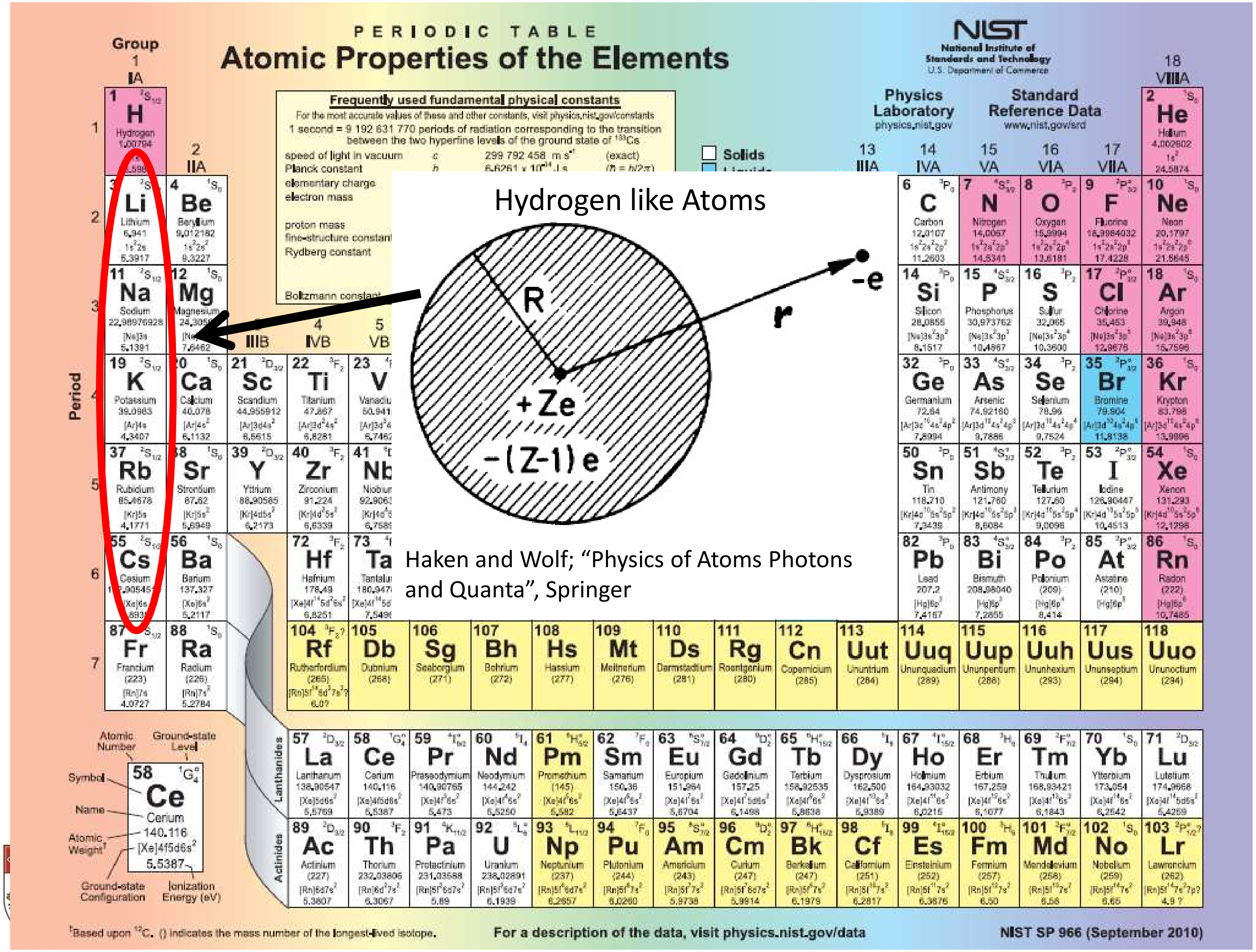
The absolute value is given by:

$$|\boldsymbol{F}| = \sqrt{F(F+1)}\,\hbar$$

The quantum numbers *F* of the total angular momentum **F** can have the values

$$F = J + I, J + I - 1 \ldots J - I$$

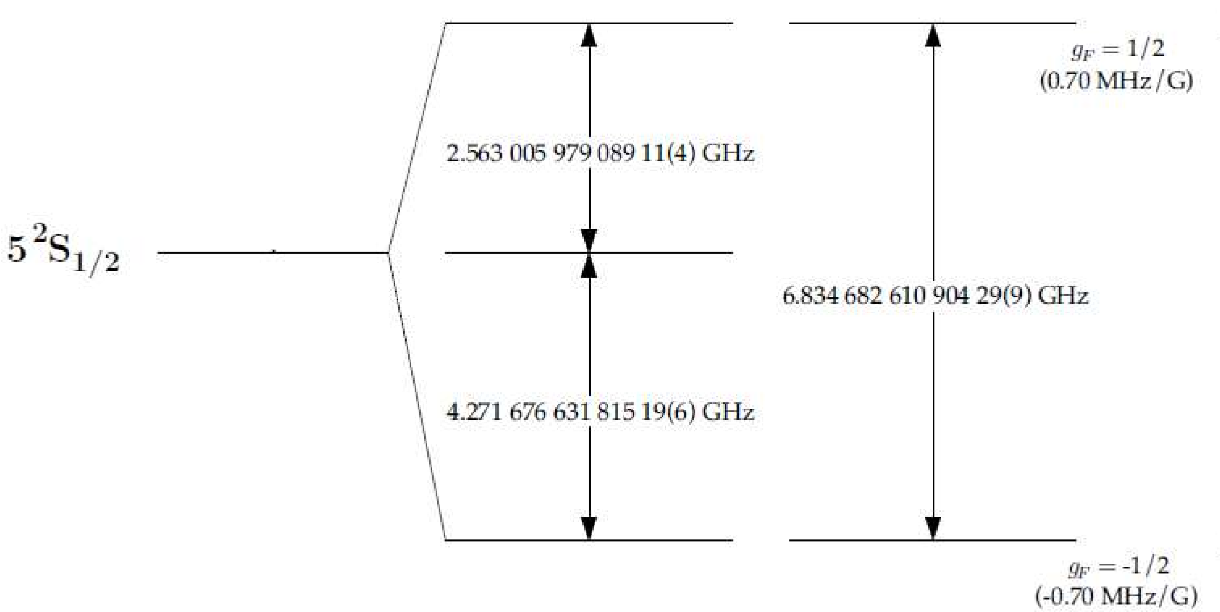
Hydrogen like Atoms



Haken and Wolf; “Physics of Atoms Photons and Quanta”, Springer

Hyperfine States

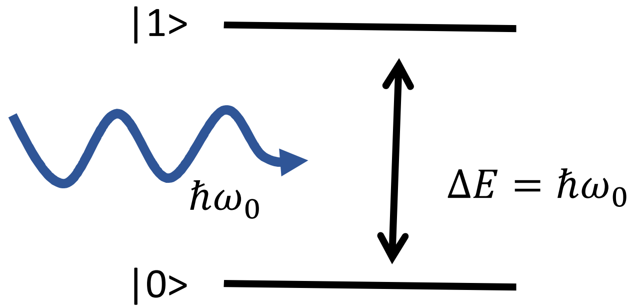
Lithium
Sodium
Potassium
Rubidium
Caesium
…



Rabi Oscillations

Coupling two level atom (Hyperfine states) to a resonant electromagnetic field:

RWA and choose phase of Ω to be real at interaction region

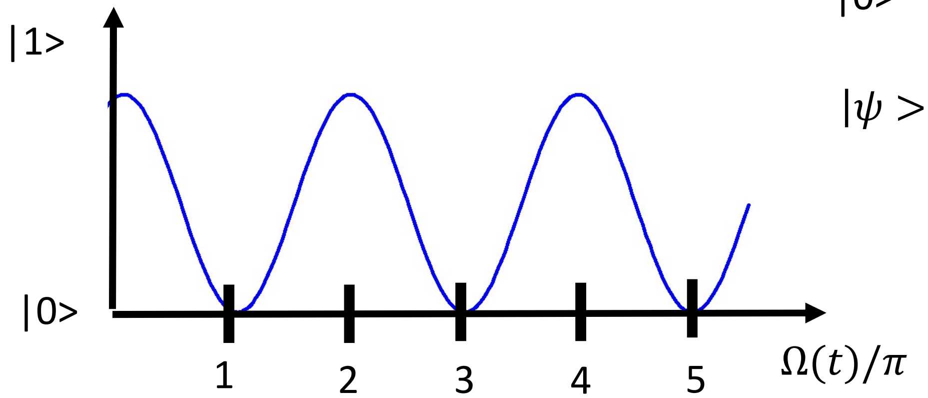


$$\begin{bmatrix}\dot{\alpha}\\ \dot{\beta}\end{bmatrix} = -i/2\begin{bmatrix}0 & \Omega(t)\\ \Omega(t) & 0\end{bmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix}$$

$$\dot{\alpha} = \frac{i}{2}\Omega\,\beta \qquad \alpha = 1$$

$$\dot{\beta} = \frac{i}{2}\Omega\,\alpha \qquad \beta = 0$$

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \begin{bmatrix}\cos(\Omega t)\\ \mathrm{i}\sin(\Omega t)\end{bmatrix}$$



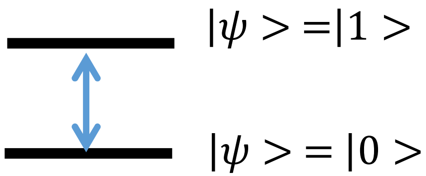
$$|\psi> = \alpha|0> + \beta|1>$$

Rabi Oscillations

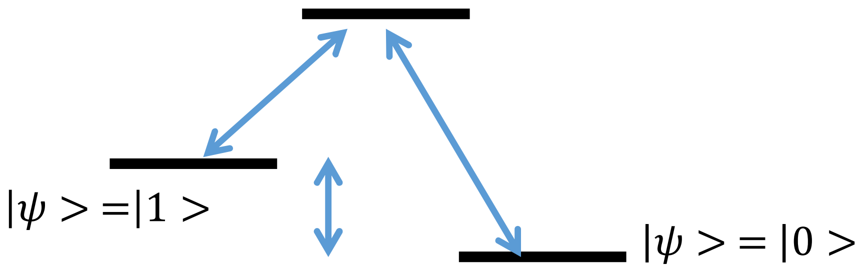
Coupling two level atom (Hyperfine states) to a resonant electromagnetic field:

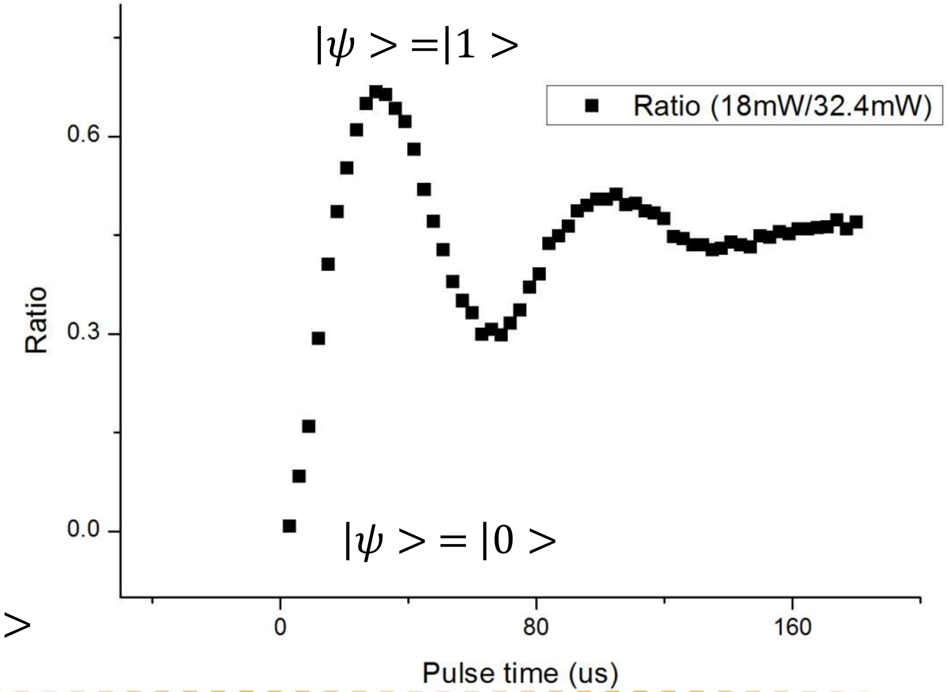
Single Qubit Gates

Single photon



Two Photon





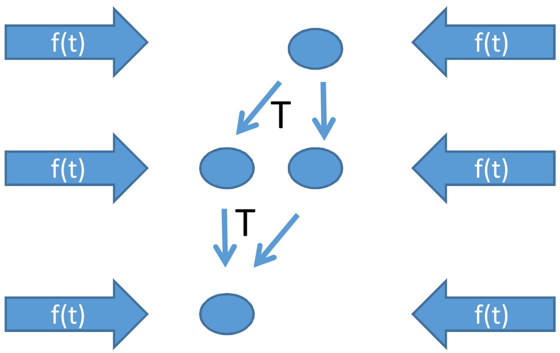
Ramsey Interferometry

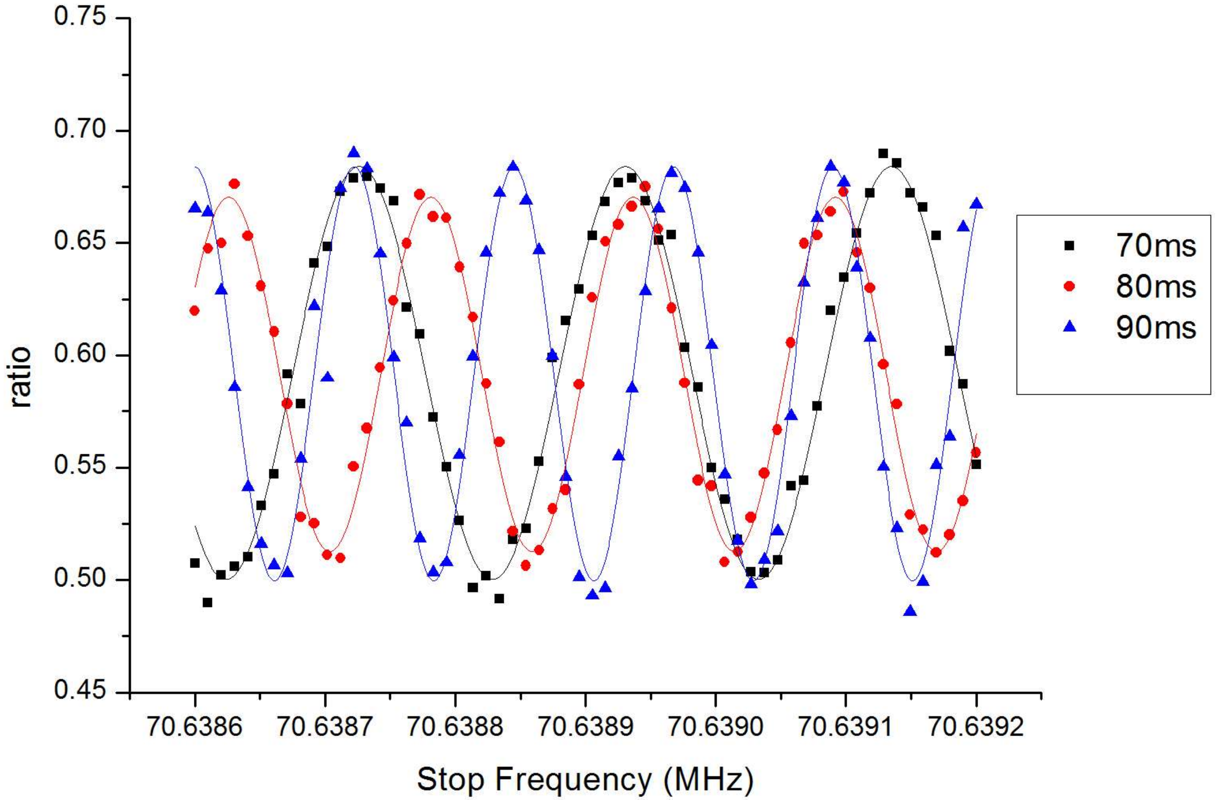
Light Matter Interaction Hamiltonian

$\pi / 2$

π

$\pi / 2$





Qubits Neutral Atoms

Qubit Realization with Neutral Atoms

Traps for Neutral Atoms

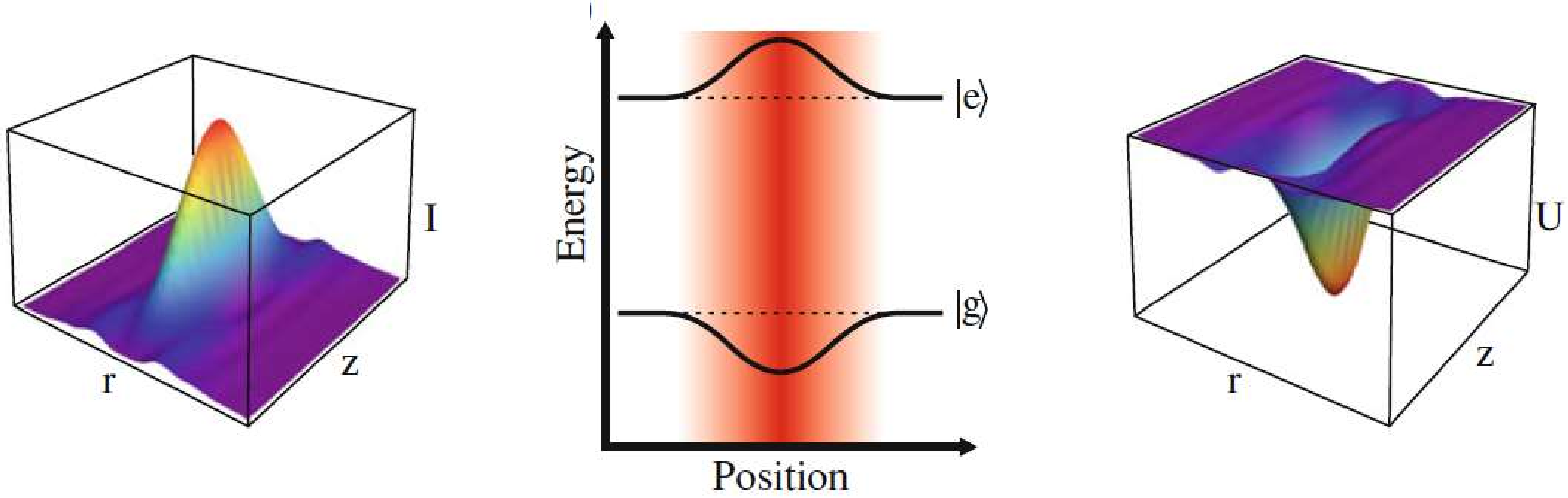
Gates with Neutral Atoms

Architectures with Neutral Atoms

Traps for Neutral Atoms

- Optical Microtraps
- Magnetic Microtraps
- Preparation

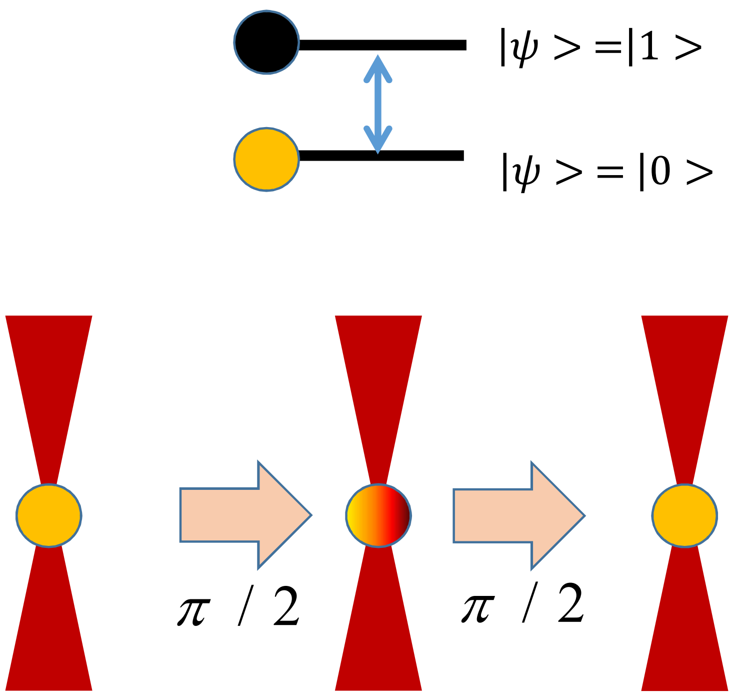
Dipole Traps

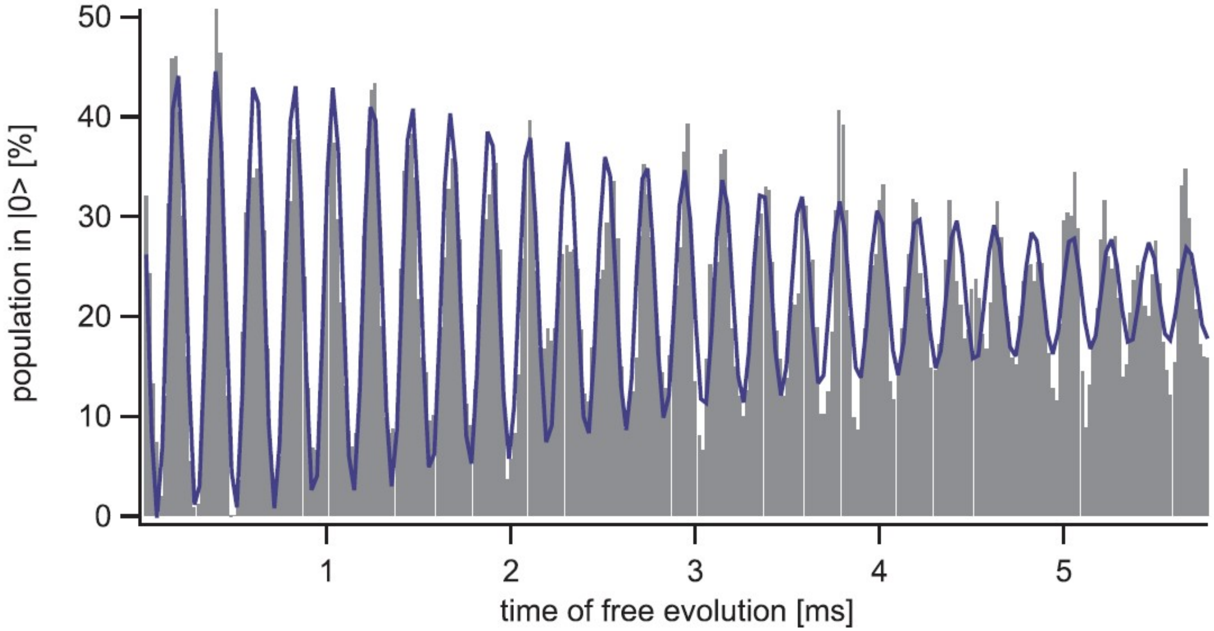


$$U(\mathbf{r}) = \frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta} I(\mathbf{r}) \quad ; \quad \Gamma_{SC}(\mathbf{r}) = \frac{3\pi c^2}{2\hbar\omega_0^3}\left(\frac{\Gamma}{\Delta}\right)^2 I(\mathbf{r})$$

M. Schlosser, S. Tichelmann, J. Kruse, G. Birkl
Quantum Inf. Process. 10, 907-924 (2011)

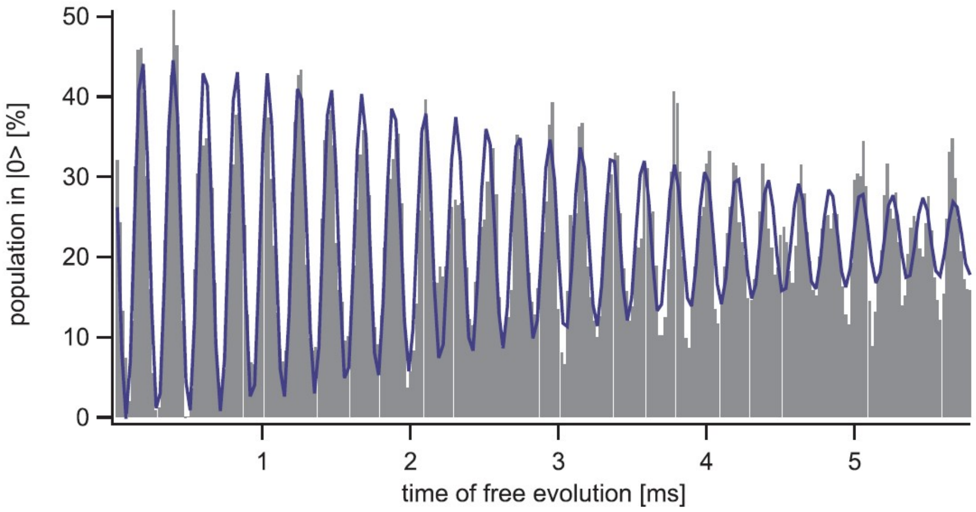
Ramsey Interferometry

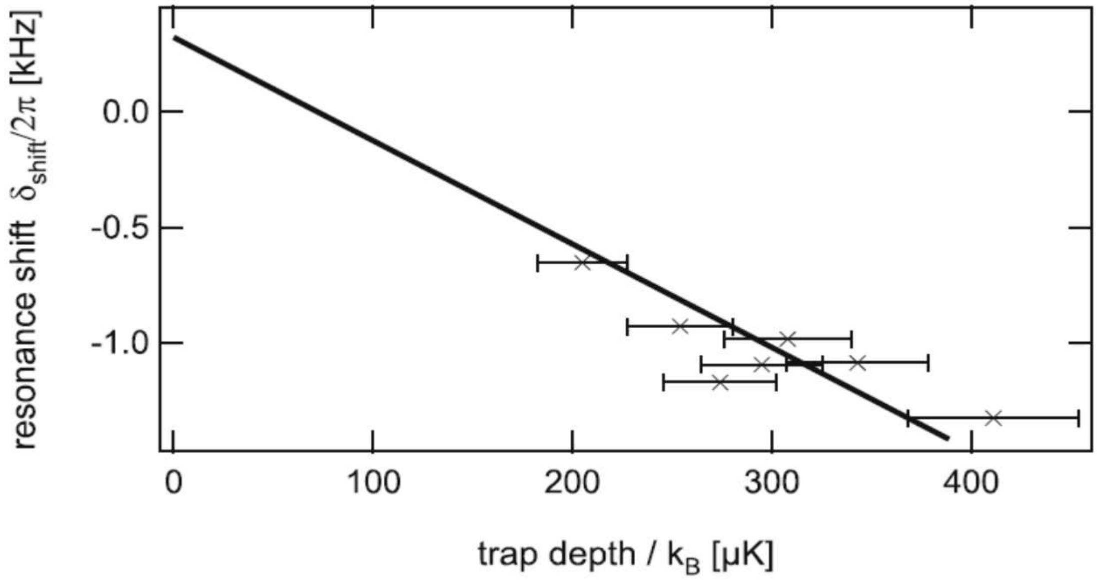


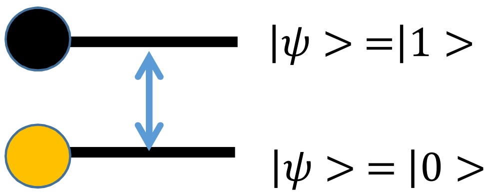


A. Lengwenus, J. Kruse, M. Volk, W. Ertmer and G. Birkl, Appl. Phys. B 86, 377–383 (2007)

Ramsey Interferometry

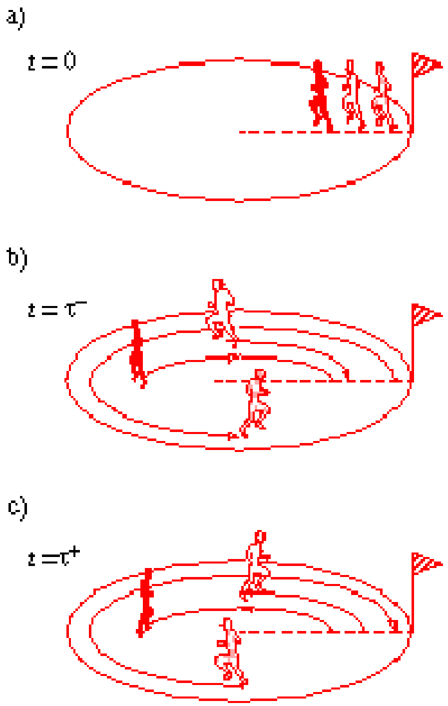


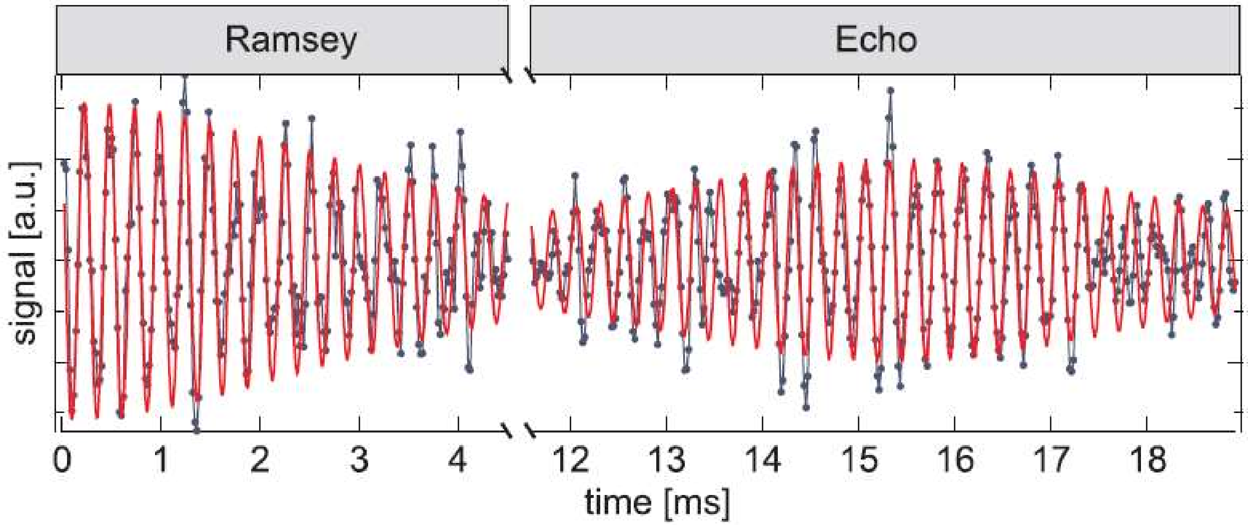




A. Lengwenus, J. Kruse, M. Volk, W. Ertmer and G. Birkl,
Appl. Phys. B 86, 377–383 (2007)

Ramsey Interferometry



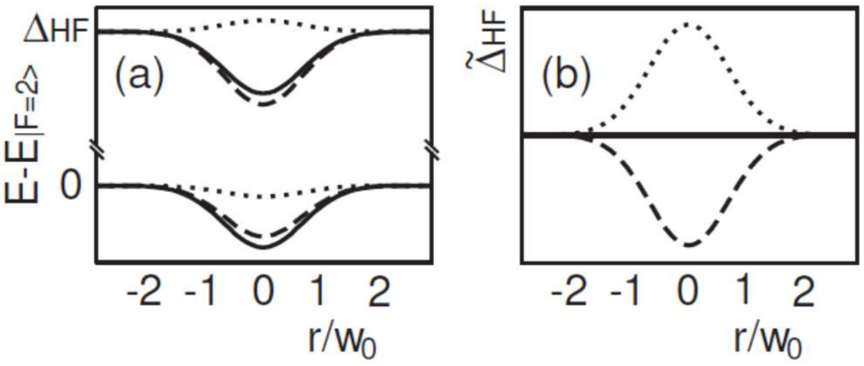


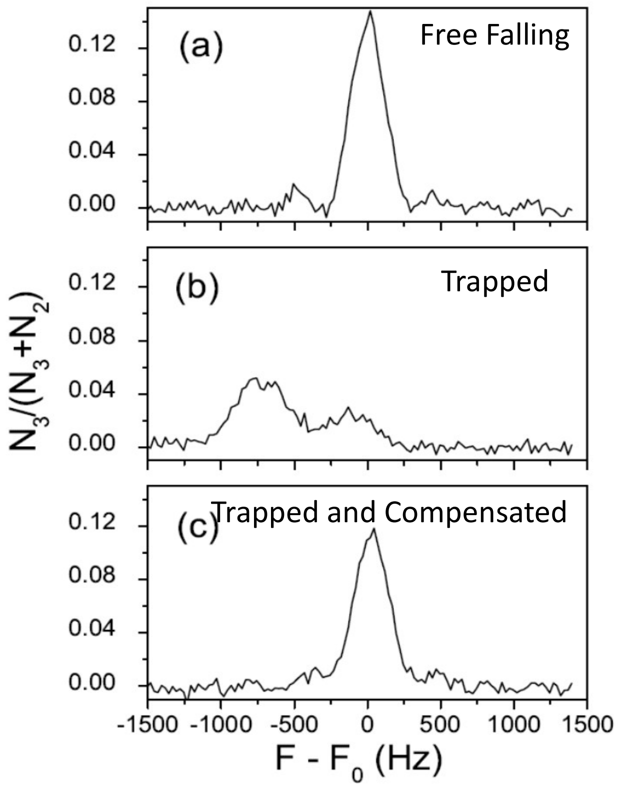
A. Ponti and A. Schweiger, "Echo phenomena in electron paramagnetic resonance spectroscopy",*Appl. Magn. Reson.* **7**, 363 (1994).

M. Schlosser, S. Tichelmann, J. Kruse, G. Birkl
Quantum Inf. Process. 10, 907-924 (2011)

Differential Light Shift

Single Beam Dipole Trap:
- Two hyperfine levels have a different ac Stark shift (dashed line).
- An additional weak laser, detuned to the middle of the hyperfine splitting, creates an additional ac Stark shift (dotted line)
- Total amount of light shift (full line) is identical for both hyperfine levels.





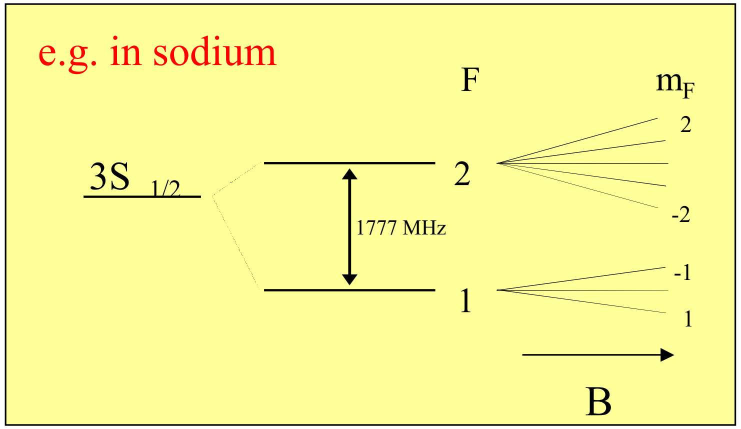
A. Kaplan, M.F. Andersen, N. Davidson, Phys. Rev. A 66, 045401 (2002)

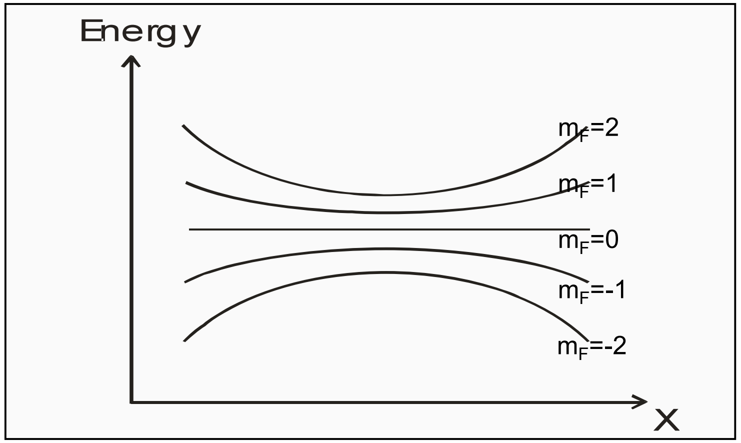
Traps for Neutral Atoms

- Optical Microtraps
- Magnetic Microtraps
- Preparation

Magnetic Trap

Create a field minimum and atoms are attracted to this field minimum.





Stability against Spin-Flip Losses

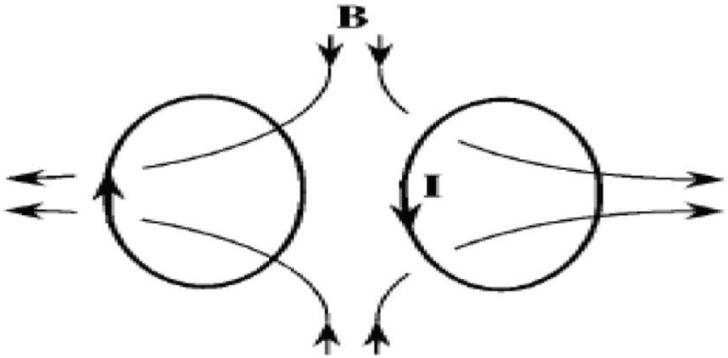
Magnetic traps only confine weak-field seeking states
-> atoms will be lost from the trap if they make a transition to a strong-field seeking state.

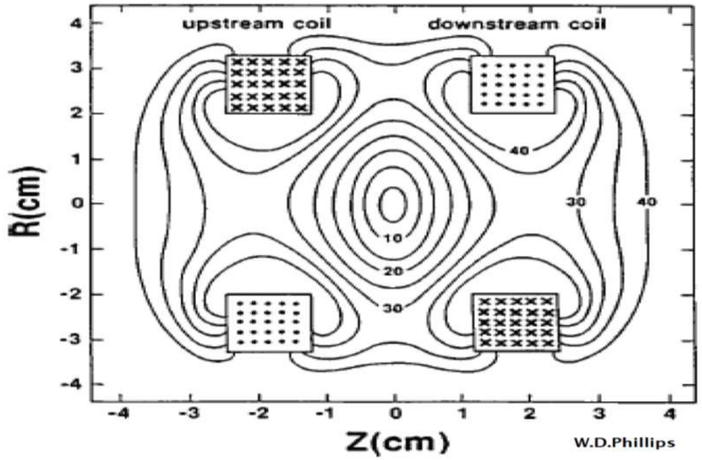
The trap is stable only if the atom's magnetic moment adiabatically follows the direction of ***B***.

This requires that the rate of change of the field's direction ϑ (in the reference frame of the moving atom) must be slower than the Larmor frequency:

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} < \frac{\mu_{\mathrm{m}}|\boldsymbol{B}|}{\hbar} = \omega_{\mathrm{L}}$$

Quadrupole Traps





$$\hat{x} \cdot \frac{d\vec{B}}{dx} = \hat{y} \cdot \frac{d\vec{B}}{dy} = -2\hat{z} \cdot \frac{d\vec{B}}{dz}$$

$$B(x,y,z) = B' \left[x\hat{x} + y\hat{y} - 2z\hat{z} \right]$$

Quadrupole Traps

Majorana transitions is inevitable in quadrupole traps.

- Loss rate depends on temperature.

Example: For atoms moving at a velocity *v*, the effective size of the "hole" in the trap is

$$\sqrt{2\hbar v / \pi \mu_{\mathrm{m}} B'}$$

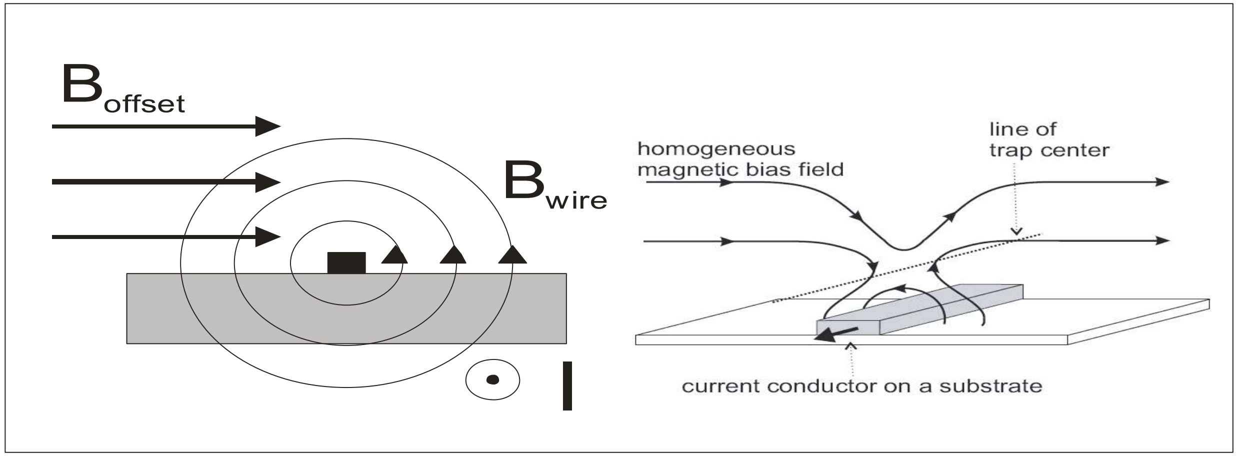
Which is about **1 µm** for $\mu_m = \mu_B$, v=1m/s and B'_0 =1000G/cm.

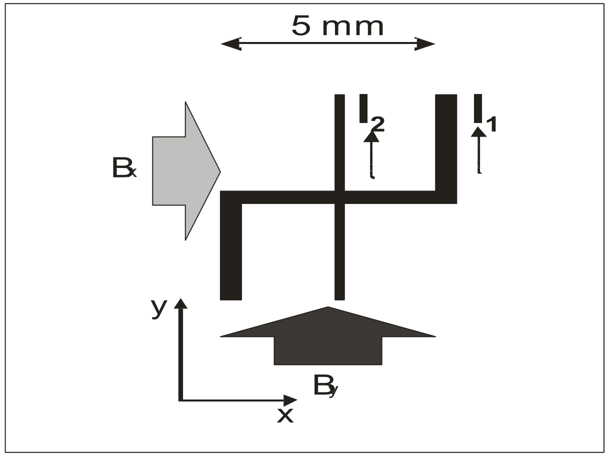
As long as the hole is small compared to the cloud diameter, the trapping time can be long (even longer than a minute), so that quadrupole traps can work very well if the atoms are not too cold.

Chip Trap

Typical Atom Chip trap design:

Magnetic Trapping





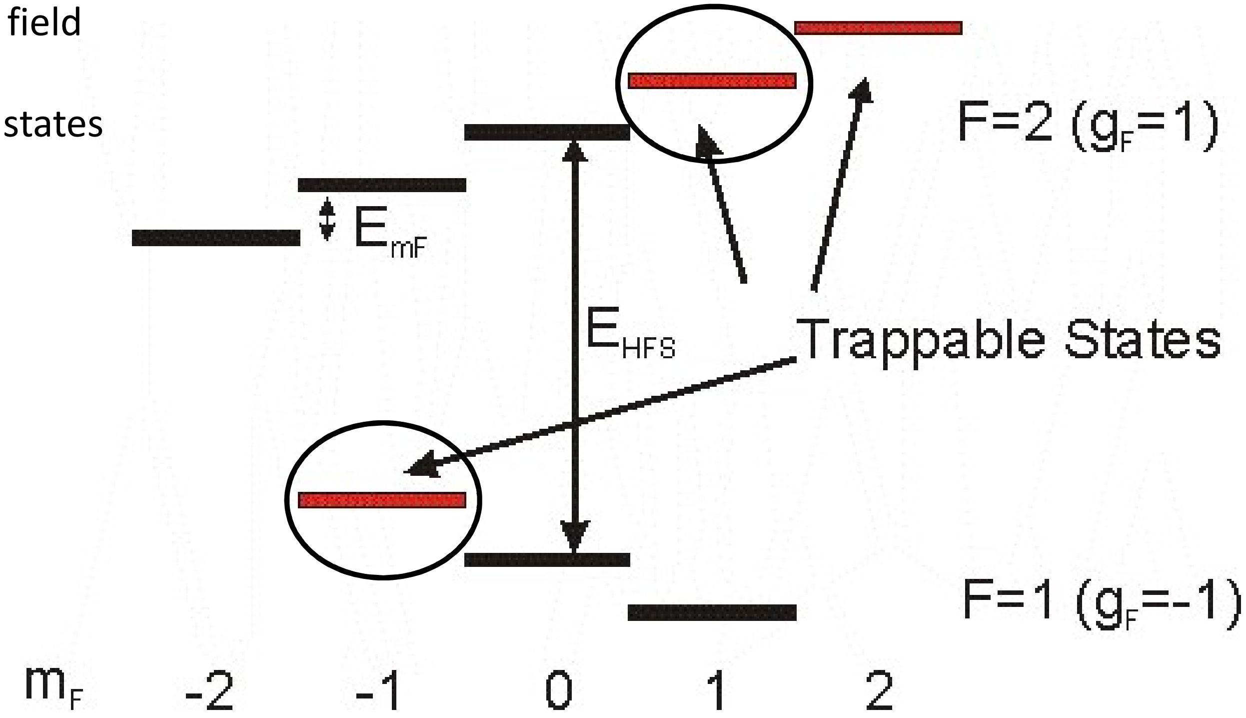
Trap atoms at distances on the μm scale to the surface.

Reviews of Modern Physics, 79(1), 235-289
Advances in Atomic, Molecular, and Optical Physics, Vol 48 **48**: 263-356

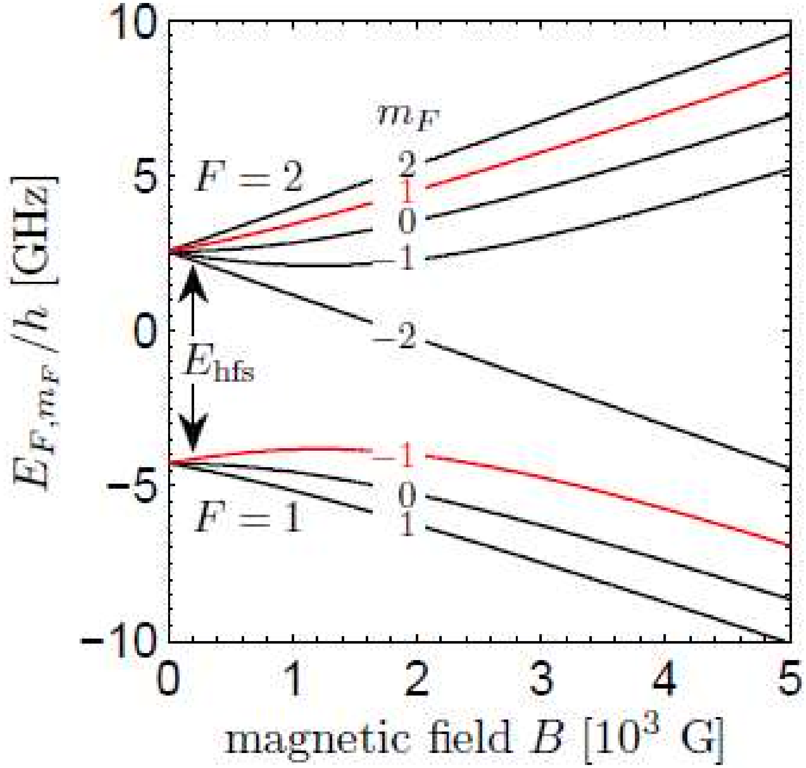
Qubit in Trapped State

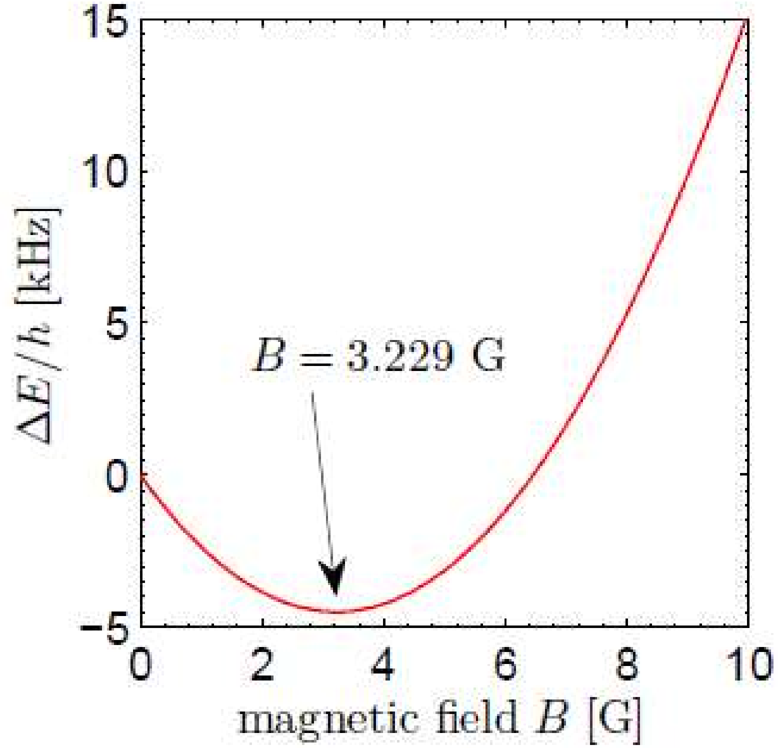
Rb 87 in weak magnetic field

Red indicates trappable states



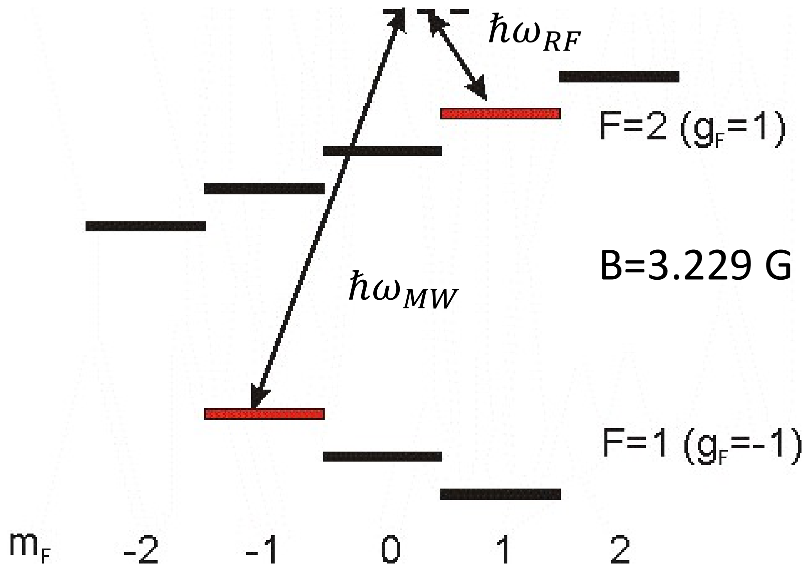
Magnetic Field Dependence

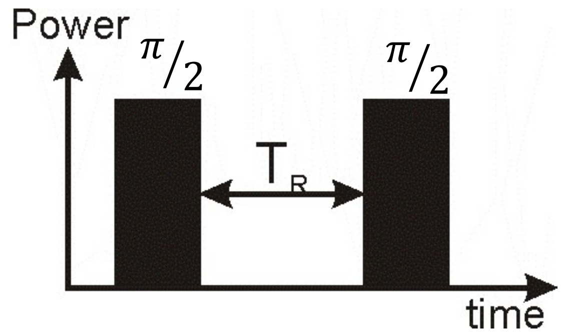


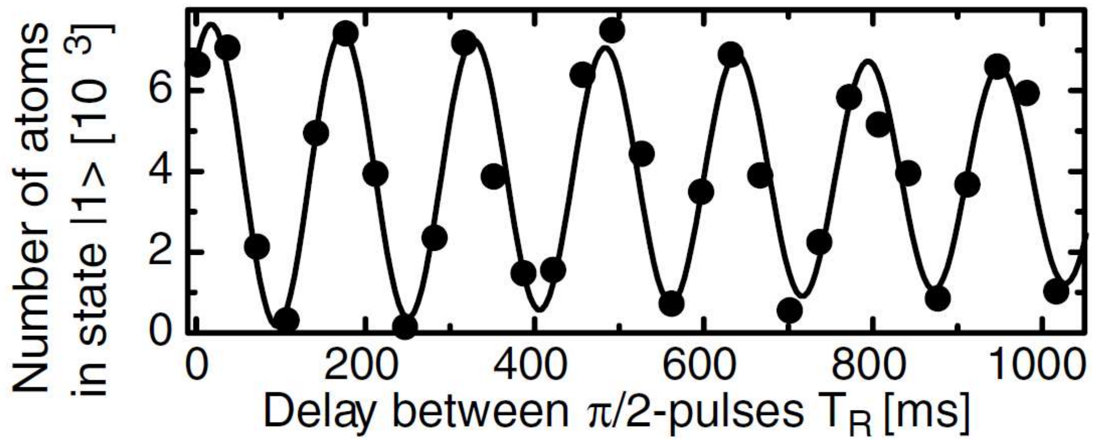


P. Treutlein, Dissertation, LMU Munich (2008)

Coherence Time





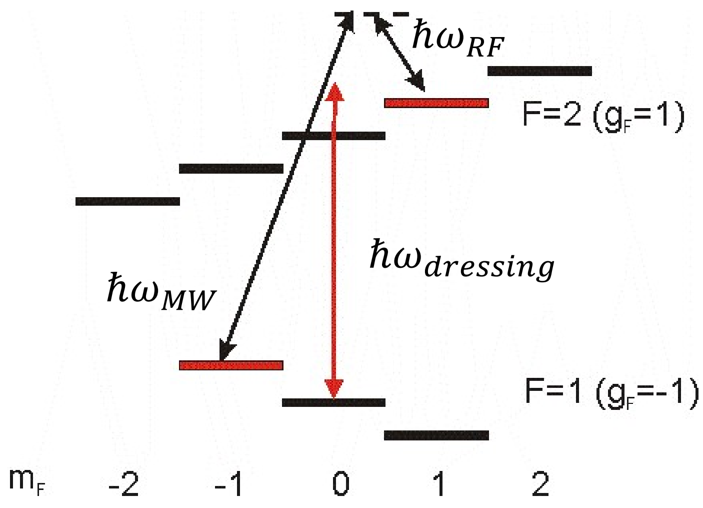


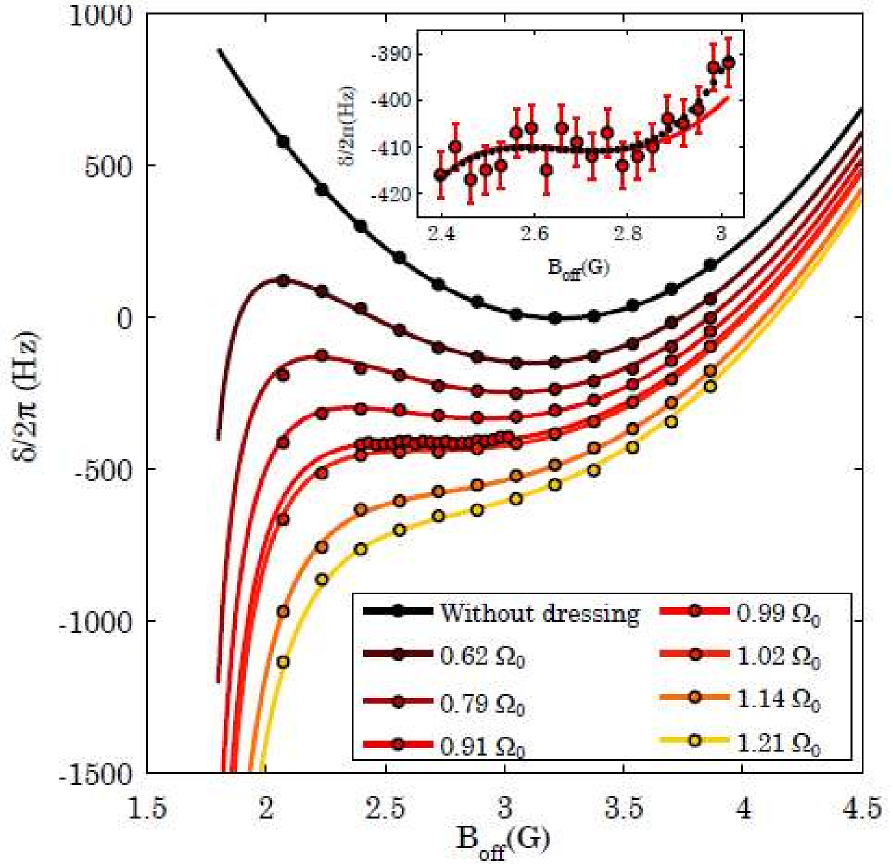
- Ramsey Spectroscopy of Rb atoms in magnetic micro trap |F=1,mF=-1> <-> |F=2,mF=1> at "magic" magnetic field

- 1/e decay time of 2.8s +/- 1.6s

P. Treutlein, P. Hommelhoff, T. Steinmetz, Th. W. Hänsch, and J. Reichel, Phys. Rev. Lett. **92**, 203005 (2004)

Dressed States





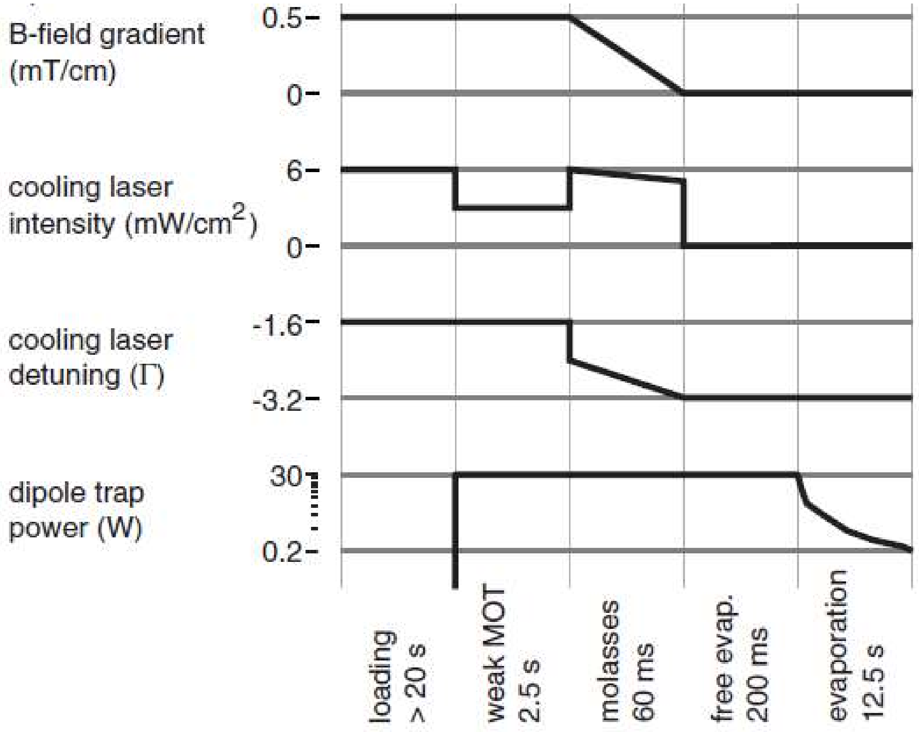
L. Sárkány, P. Weiss, H. Hattermann, and J. Fortágh; Phys. Rev. A **90**, 053416 (2015)

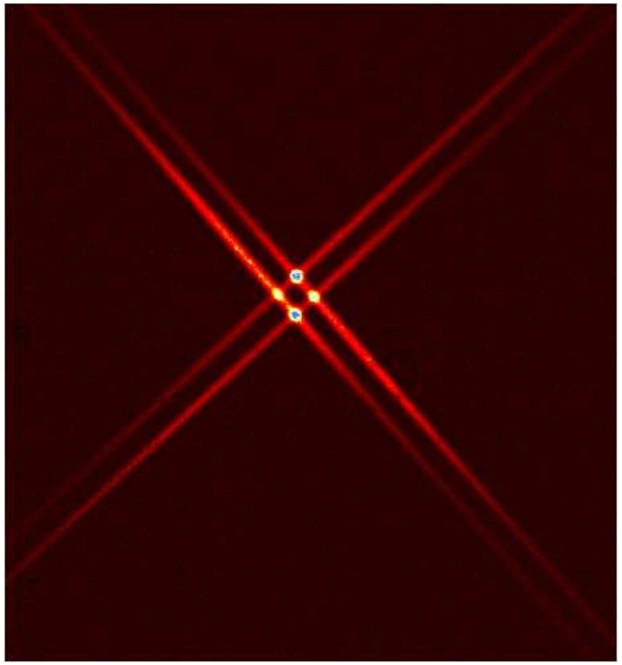
Traps for Neutral Atoms

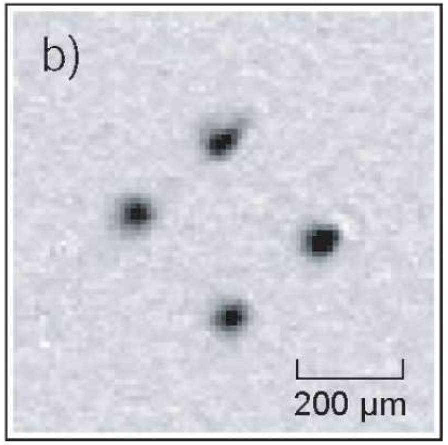
- Optical Microtraps
- Magnetic Microtraps
- Preparation

Experimental Sequence

Typical experimental sequence in an ultra cold atom experiment loading a dipole trap:







R Dumke, M Johanning, E Gomez, J D Weinstein, K M Jones and P D Lett; New Journal of Physics, 8, (2006)

Photoassociation

- Long range S+S potential ~ R^6.

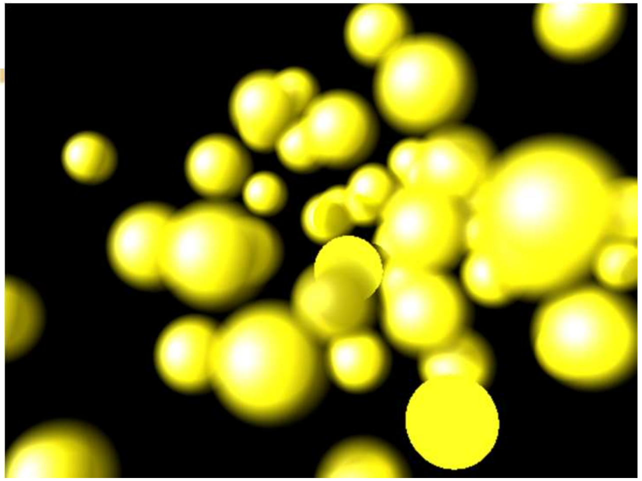
- Long range S + P potential ~ R^3.

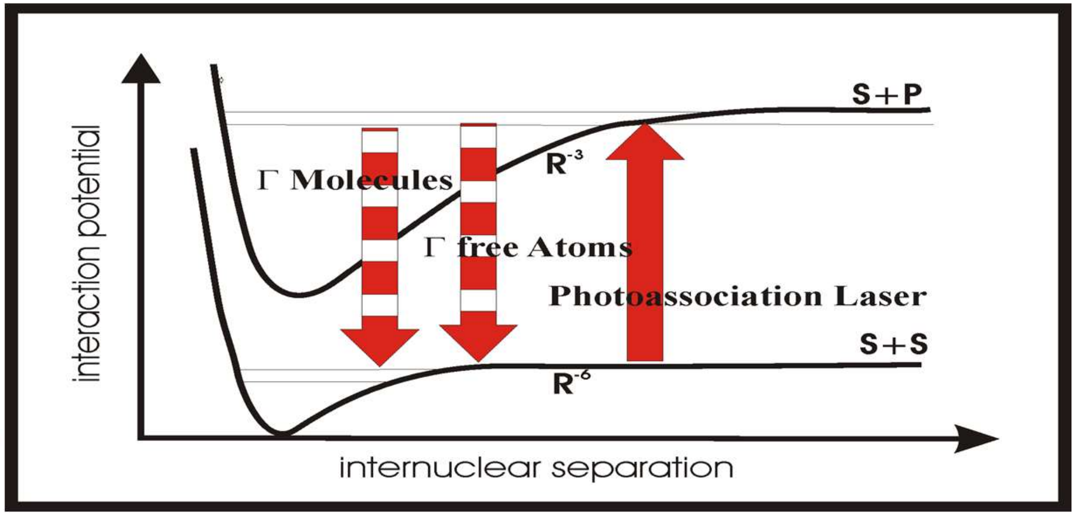
- Outer turning points located where S+S potential is flat.

- Transitions free atoms bound molecules induced by laser.

- The excited state decays:
  unbound atoms / ground state molecules.

- The molecules can be measured:
  trap loss
  resonantly ionizing

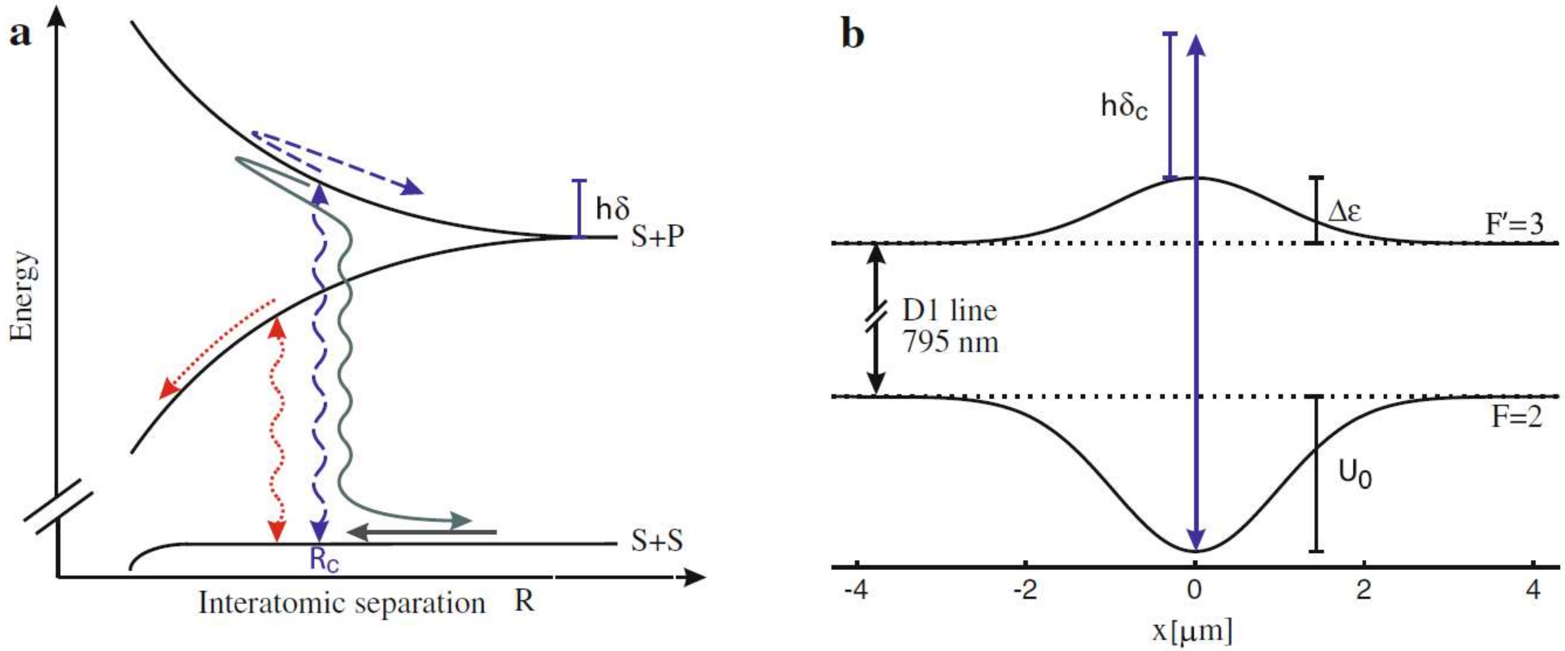




R. Dumke, J. D. Weinstein, M. Johanning, K. M. Jones, and P. D. Lett Phys. Rev. A **72**, 041801(R) (2005)

Light-Assisted Collisions

General Picture Light Assisted collisions with blue detuning



T. Grünzweig, M. McGovern, A. J. Hilliard, M. F. Andersen; Quantum Information Processing; Vol 10 Iss 6, 925-940 (2011)

Centre for Quantum Technologies

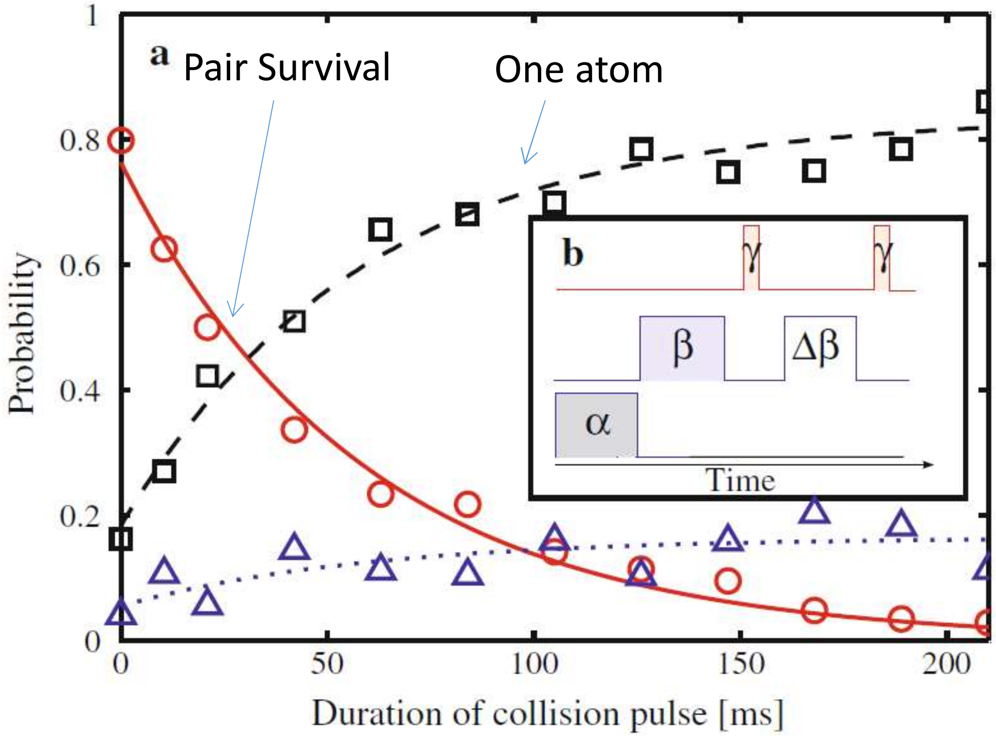
Blue-detuned light-assisted collisions

- 50 atoms are loaded into the microtrap (α).

- preparation light-assisted collision pulse reduce the number of atoms until few remain (β).

- atoms are imaged and counted before and after (γ) the variable light-assisted collision pulse (Δβ)

- peak loading efficiency of 86.3%



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T. Grünzweig, M. McGovern, A. J. Hilliard, M. F. Andersen; Quantum Information Processing; Vol 10 Iss 6, 925-940 (2011)

Qubit Realization with Neutral Atoms

Traps for Neutral Atoms

Gates with Neutral Atoms

Architectures with Neutral Atoms