Adiabatic potentials

Hélène Perrin

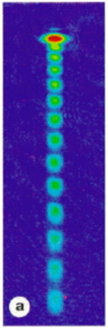
Laboratoire de physique des lasers, CNRS-Université Paris 13
Sorbonne Paris Cité

Manipulation of quantum degenerate gases
Les Houches, September 16–27, 2013

Context

Quantum gases (course of Mischa Baranov) are outstanding systems for two main kind of applications:

- precision measurements
  BEC = coherent matter wave, atom lasers available ⇒ atom interferometry
  See Thorsten Schumm course

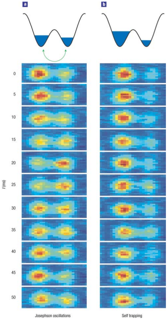


Munich 2000

Context

Quantum gases (course of Mischa Baranov) are outstanding systems for two main kind of applications:

- precision measurements
  BEC = coherent matter wave, atom lasers available $\Rightarrow$ atom interferometry
  See Thorsten Schumm course
- modeling other systems: quantum simulators
  Quantum gases provide controllable, tunable quantum systems: model for solid state physics (optical lattices, 1D/2D: I. Bouchoule/M. Holzmann, magnetism, hydrodynamics: S. Stringari, equation of state, out of equilibrium dynamics: A. Polkovnikov...)
  Feynman's idea of a quantum simulator is within reach.



Heidelberg 2005

Tuning quantum gases

A wide range of tunable parameters:

- temperature in the range 10 nK – 1 μK (P. Verkerk / J. Walraven)
- interaction strength: scattering length a (J. Walraven)
- dynamical control of the confinement geometry
- periodic potentials (optical lattices)
- low dimensional systems accessible (1D, 2D) (I. Bouchoule / M. Holzmann)
- several internal states or species available
- easy optical detection (J. Reichel)

Using adiabatic potentials

This course: what adiabatic potentials are useful for:

- temperature in the range 10 nK – 1 μK (P. Verkerk / J. Walraven)
- interaction strength: scattering length a (J. Walraven)
- dynamical control of the confinement geometry
- periodic potentials (optical lattices)
- low dimensional systems accessible (1D, 2D) (I. Bouchoule / M. Holzmann)
- several internal states or species available
- easy optical detection (J. Reichel)

Using adiabatic potentials

This course: what adiabatic potentials are useful for:

- temperature in the range 10 nK – 1 μK (P. Verkerk / J. Walraven)
- interaction strength: scattering length a (J. Walraven)
- dynamical control of the confinement geometry
- periodic potentials (rf lattices)
- low dimensional systems accessible (1D, 2D) (I. Bouchoule / M. Holzmann)
- several internal states or species available
- easy optical detection (J. Reichel)

Outline of the course

1. **Basics of spins in fields**
   - a few examples of adiabatic potentials (slides)
   - spin rotation
   - spin in a static magnetic field
   - effect of a classical rf field; RWA
   - influence of the rf polarization
   - rf field quantization: the dressed atom picture
2. **Adiabatic potentials for rf-dressed atoms**
   - position-dependent fields: adiabatic potentials
   - discussion of a few interesting configurations
   - loading atoms in an AP: phase and frequency jumps
   - effect of noise in the rf source
   - Landau-Zener losses
3. **Going further**
   - time averaged adiabatic potentials (TAAP)
   - adding a second rf field: spectroscopy and evaporation
   - beyond RWA

Prehistory of adiabatic potentials

Trapping with a microwave

Spreeuw et al., PRL **72**, May 1994:

VOLUME 72, NUMBER 20 PHYSICAL REVIEW LETTERS 16 MAY 1994

Demonstration of Neutral Atom Trapping with Microwaves

R. J. C. Spreeuw, C. Gerz, Lori S. Goldner, W. D. Phillips, S. L. Rolston, and C. I. Westbrook*
National Institute of Standards and Technology, PHY A-167, Gaithersburg, Maryland 20899

M. W. Reynolds† and Isaac F. Silvera
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 4 November 1993)

We demonstrate trapping of neutral Cs atoms by the magnetic dipole force due to a microwave field. The trap is formed in a spherical microwave cavity tuned near the ground state hyperfine transition (9.193 GHz). With a microwave power of 83 W, the trap is ≈ 0.1 mK deep. It is loaded with Cs atoms laser cooled to ≈ 4 μK. We observe oscillatory motion of atoms in the trap at frequencies of 1–3 Hz. This type of trap has certain advantages for achieving the conditions for Bose-Einstein condensation in hydrogen or the alkalis, because it can confine atoms predominantly in the lowest energy spin state.

Trapping with an inhomogeneous microwave field in a static magnetic field.

Prehistory of adiabatic potentials

Trapping with a microwave

[Spreeuw 1994]

The potential for the atoms in the trapping state, due to static magnetic, microwave, and gravitational fields, is

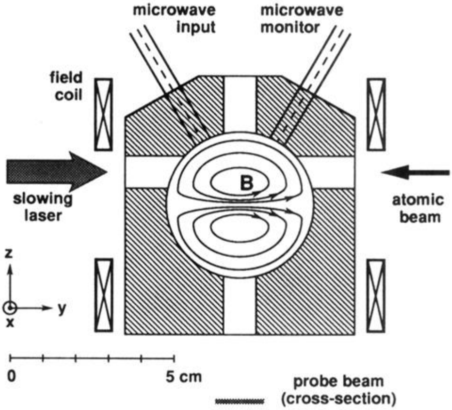
$$U(\mathbf{r}) = -\bar{\mu}B(\mathbf{r}) - \tfrac{1}{2}\hbar\,\Omega(\mathbf{r}) + mgz\ ,$$

where mgz is the gravitational energy, $\boxed{\Omega = (\omega_R^2 + \delta^2)^{1/2}}$, with the Rabi frequency $\omega_R(\mathbf{r}) = \mu_\perp b_\perp(\mathbf{r})/\hbar$ and the detuning $\delta(\mathbf{r}) = 2\mu_z[B_{\text{res}} - B(\mathbf{r})]/\hbar$, both functions of position; $b_\perp$ is the amplitude of the rf field transverse to the

The trapping potential is given by the microwave coupling $\omega_R(\mathbf{r})$ and detuning $\delta(\mathbf{r}) = \omega_{\text{mw}} - \mu B(\mathbf{r})$.

Prehistory of adiabatic potentials
Trapping with a microwave

[Spreeuw 1994]



Prehistory of adiabatic potentials
Trapping with a microwave

[Spreeuw 1994]

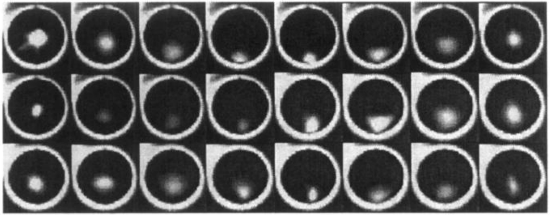


FIG. 3. Sequence of images with 67 ms successive increase in trapping time. The bright ring is a 1 cm diameter observation hole in the side of the cavity. For this sequence the microwave power level was 42 W.

Cs atoms oscillating in the microwave + magnetic field trap

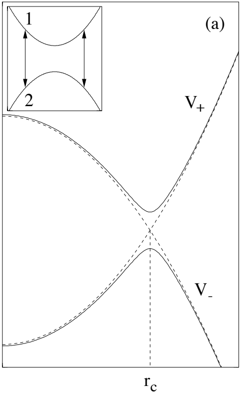
Principle of rf-induced adiabatic potentials
Trapping to an isomagnetic surface

First proposal with rf fields: O. Zobay and B. Garraway, PRL **86**, 1195 (2001):

$$\mathbf{B}_0(\mathbf{r}) + \mathbf{B}_1 \cos \omega t$$

inhomogeneous magnetic field + rf field

strong coupling regime (large B_1)
$\Rightarrow$ avoided crossing at the resonance points



Principle of rf-induced adiabatic potentials

Trapping to an isomagnetic surface

First proposal with rf fields: O. Zobay and B. Garraway, PRL **86**, 1195 (2001):

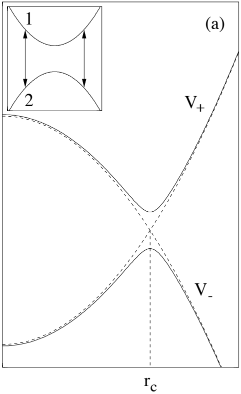
$$\mathbf{B}_0(\mathbf{r}) + \mathbf{B}_1 \cos \omega t$$

inhomogeneous magnetic field + rf field

strong coupling regime (large B_1)
$\Rightarrow$ avoided crossing at the resonance points

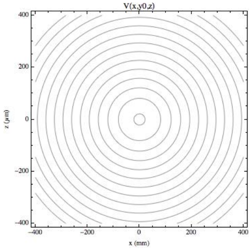
atoms trapped at the isomagnetic surface of an inhomogeneous magnetic field set by ω:

$$\text{surface} \quad B_0(\mathbf{r}) = \frac{\hbar}{|g_F|\mu_B}\,\omega.$$



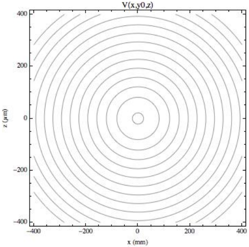
Trapping to an isomagnetic surface
Bubbles and double wells

magnetic landscape: iso-B surfaces

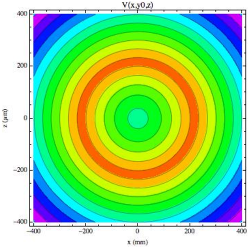


Trapping to an isomagnetic surface
Bubbles and double wells

magnetic landscape: iso-B surfaces

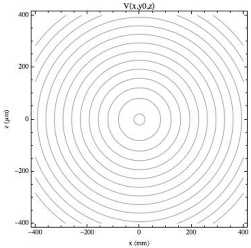


$\mathbf{B}_1$ rf on selecting the iso-B surface

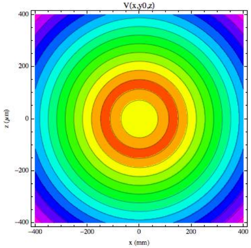


Trapping to an isomagnetic surface
Bubbles and double wells

magnetic landscape: iso-B surfaces

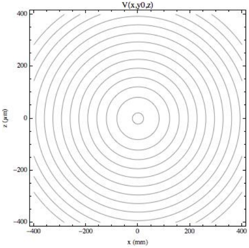


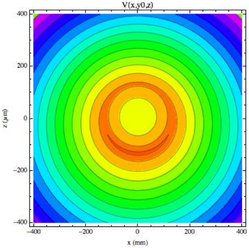
$\mathbf{B}_1$ rf on selecting the iso-B surface



Trapping to an isomagnetic surface
Bubbles and double wells

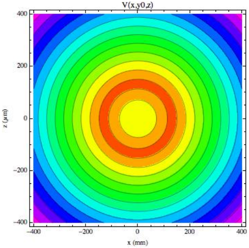
magnetic landscape: iso-B surfaces





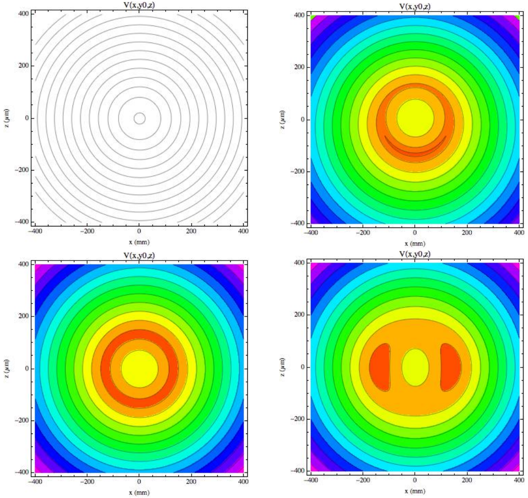
gravity on: flat trap

$\mathbf{B}_1$ rf on selecting the iso-B surface



Trapping to an isomagnetic surface
Bubbles and double wells

magnetic landscape: iso-B surfaces



gravity on: flat trap

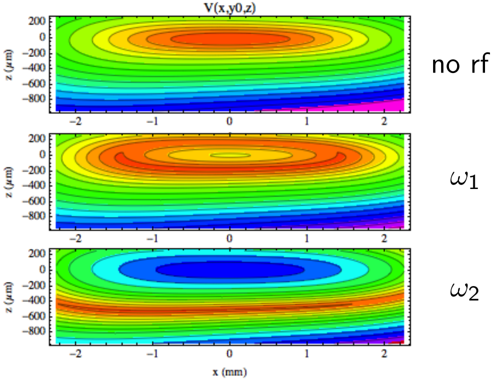
$\mathbf{B}_1$ rf on selecting the iso-B surface

inhomogeneous rf coupling $\mathbf{B}_1(\mathbf{r})$: double well

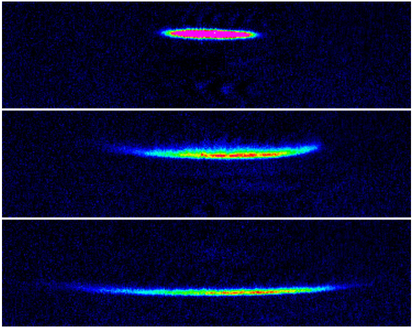
Example 1: The dressed Ioffe-Pritchard trap

First experimental realization

A "bubble trap" in the presence of gravity



calculated isopotential lines

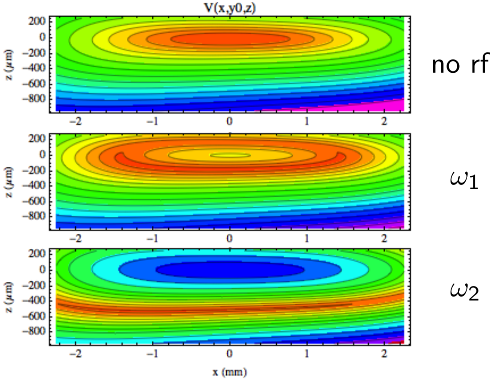


experiment: Colombe et al., EPL **67**, 593 (2004)

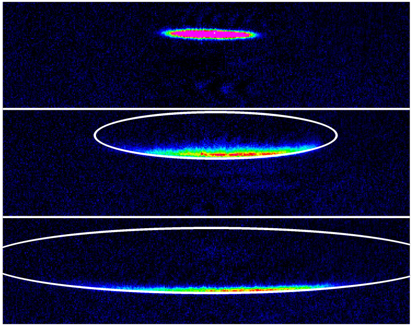
Example 1: The dressed Ioffe-Pritchard trap

First experimental realization

A “bubble trap” in the presence of gravity



calculated isopotential lines

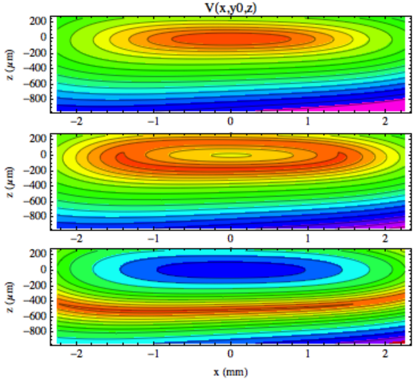


experiment: Colombe et al., EPL **67**, 593 (2004)

Example 1: The dressed Ioffe-Pritchard trap

First experimental realization

Seing the bubble structure

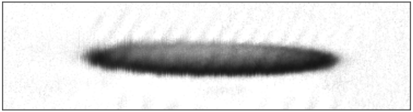


no rf

ω_1

ω_2

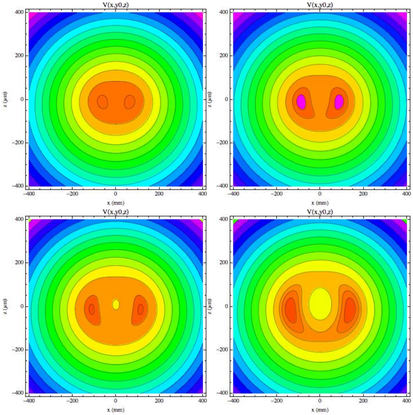
calculated isopotential lines

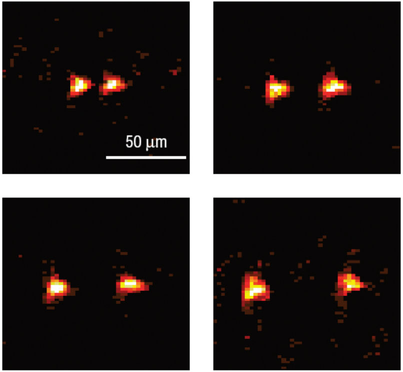


at larger temperature

Example 2: A double well potential on an atom chip
Playing with rf gradients

With an inhomogeneous rf coupling: double well potential



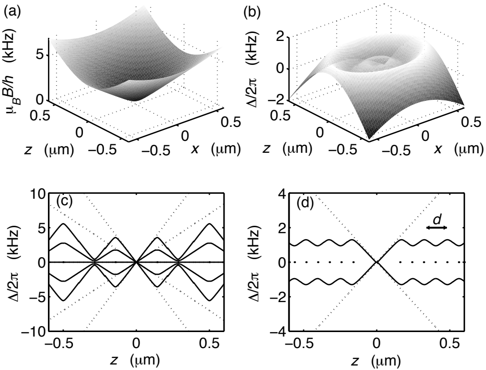


[Schumm et al., Nat. Phys. 2005]

Well separation adjusted with the rf frequency.

Example 3: A rf lattice
Multiple rf frequencies

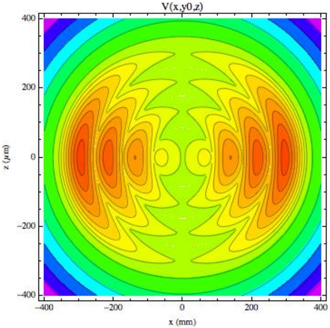
Select several iso-B surfaces with multiple rf frequencies



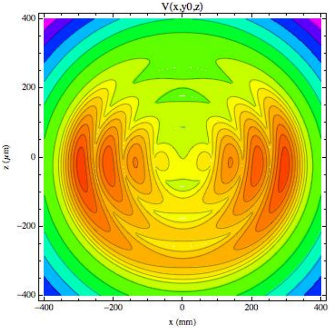
Proposal: [Courteille et al., J. Phys. B 2006]

Example 3: A rf lattice
Multiple rf frequencies

rf lattice: computed potential for 4 equidistant frequencies



without gravity

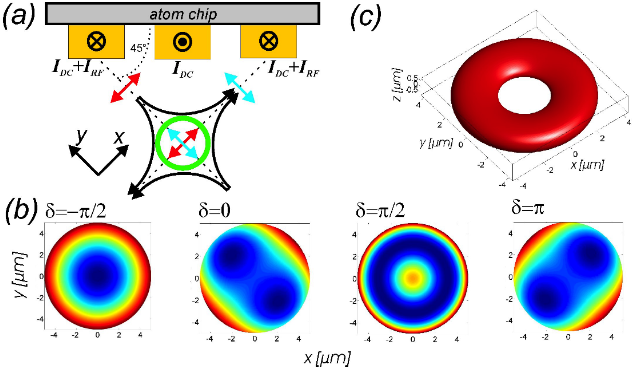


with gravity

Example 4: A ring trap

Playing with rf polarization

With a circular rf polarization: annular potential



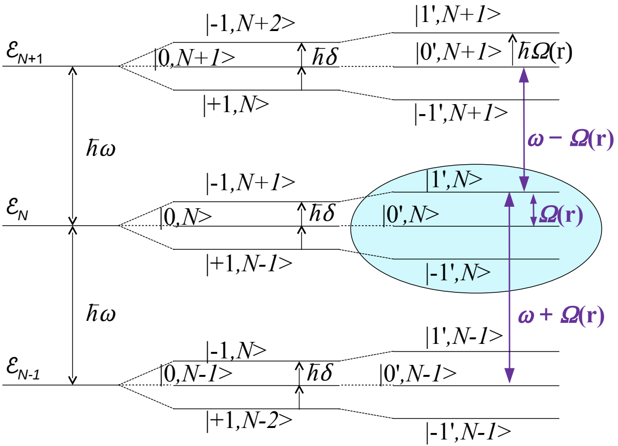
Proposal: [Lesanovsky et al., PRA 2006]

Adiabatic potentials

Illustrations of Lecture 2: rf spectroscopy / beyond RWA

Rf spectroscopy

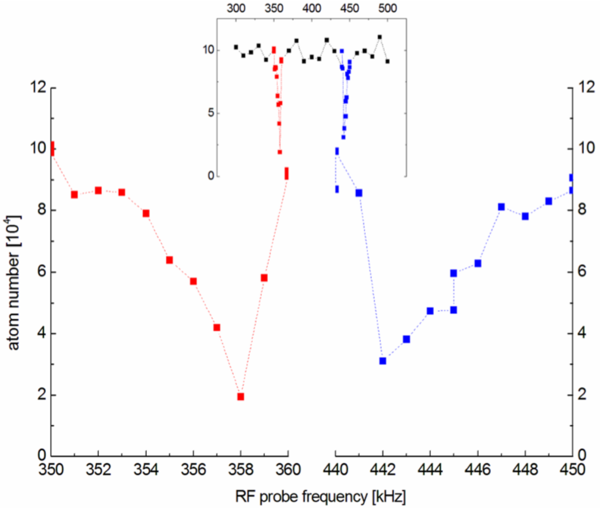
Coupling between dressed states with a weak rf probe



Rf spectroscopy

Spectroscopy of an ultracold gas in a dressed quadrupole trap

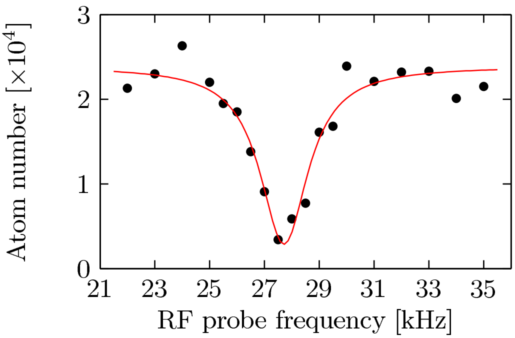
Two peaks at $\omega_{\text{probe}} \pm |\Omega_+| \Rightarrow |\Omega_+| = 2\pi \times 42 \pm 1$ kHz.



Rf spectroscopy

Spectroscopy of a BEC in a dressed quadrupole trap

Single peak at $\omega_{\text{probe}} = |\Omega_+| \Rightarrow |\Omega_+| = 2\pi \times 27.1 \pm 0.1$ kHz



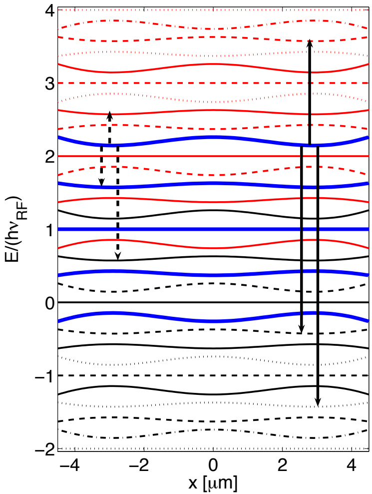
Merloti et al., NJP **15**, 033007 (2013)

Beyond RWA
Dressed levels at large coupling

Dressed levels at large $\Omega_\pm$:

$\omega = 2\pi \times 600 kHz$
$\Omega_\pm = 0$ up to above $\omega/2$

Hofferberth et al., PRA **76**, 013401 (2007) [Vienna]

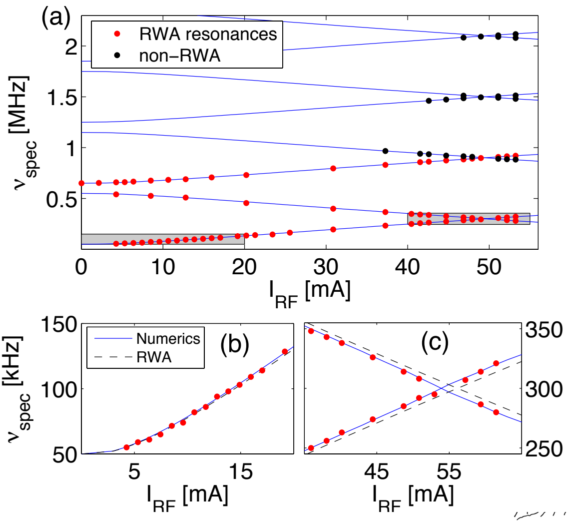


Beyond RWA

Spectroscopy in an atom chip adiabatic potential

Hofferberth et al., PRA **76**, 013401 (2007) [Vienna]

Shift from RWA predictions.



Adiabatic potentials

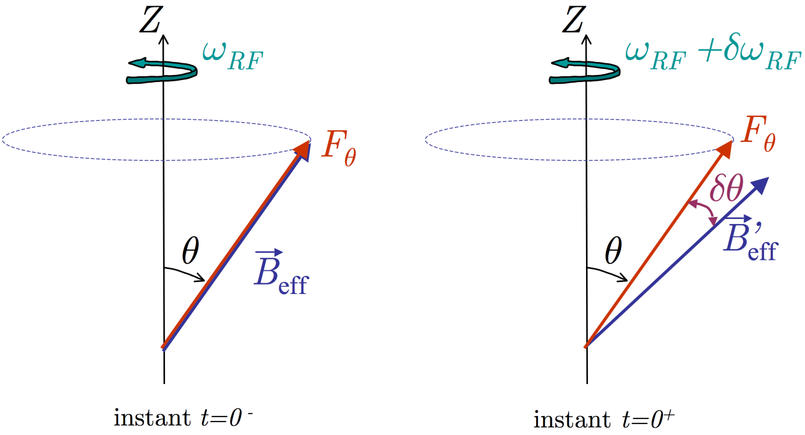
Illustrations of Lecture 3: frequency / phase jumps; frequency noise

Figures from Morizot et al., EPJD **47**, 209 (2008)

Phase and frequency jumps

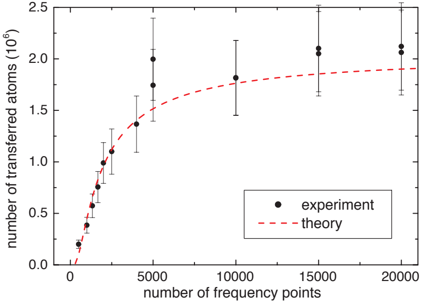
Frequency jumps

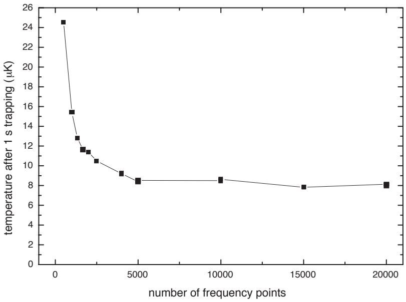
Effect of a frequency jump on the spin direction:



Phase and frequency jumps
Frequency jumps

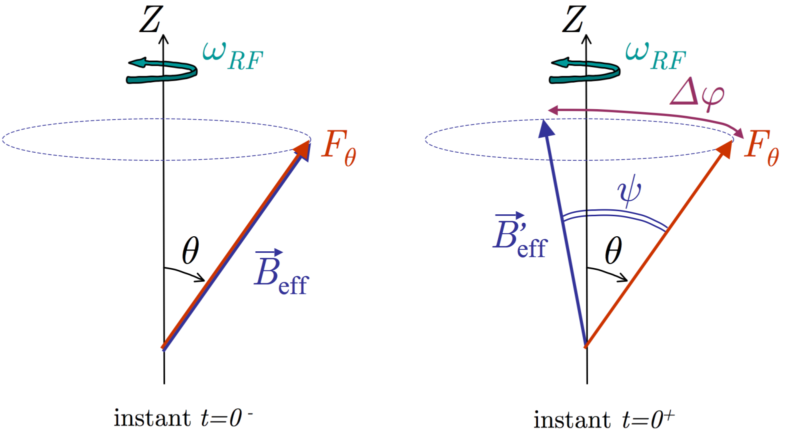
Frequency sweep done by a ramp with N discrete frequency points.





Phase and frequency jumps
Phase jumps

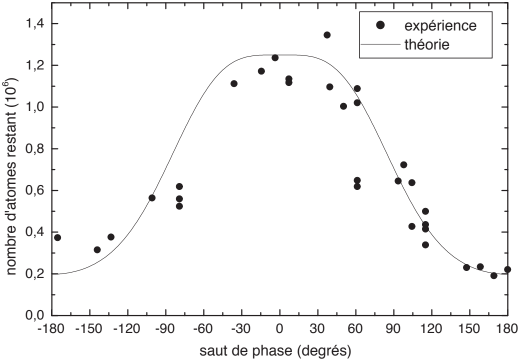
Effect of a phase jump on the spin direction:



Phase and frequency jumps

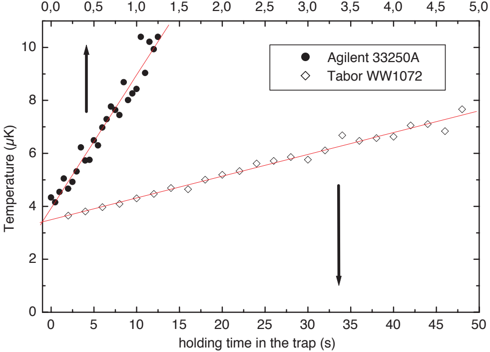
Phase jumps

Effect of a phase jump on the spin direction:



Frequency noise

Effect of a frequency noise on the temperature of a thermal cloud:



$$\dot{E} = \frac{1}{4} M\omega_z^4 \, \alpha^2 \omega^2 S_{\mathrm{rel}}(\nu_z)$$

$S_{\mathrm{rel}}(\nu_z)$: power spectral density of the relative rf frequency noise at the frequency of the trap.

Adiabatic potentials

Illustrations of Lecture 3: dressed quadrupole trap

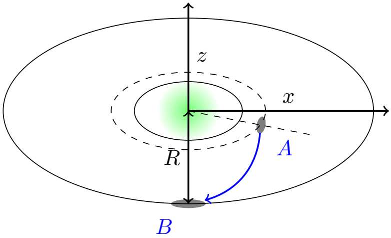
Figures from Merloti et al., NJP **15**, 033007 (2013)

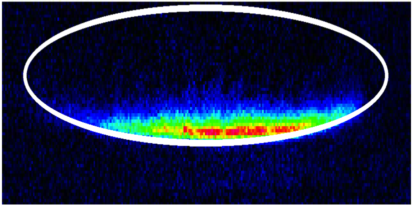
rf-induced adiabatic potentials

The dressed quadrupole trap

Adiabatic potentials for rf-dressed atoms:
the dressed quadrupole trap

- smooth potentials (magnetic fields with large coils)
- naturally very anistropic
- geometry can be modified dynamically



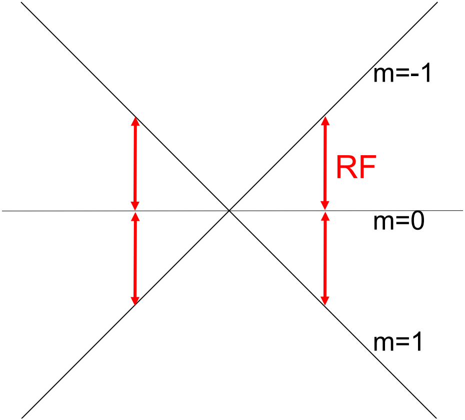


Atoms are confined to the isopotentials of a quadrupole field.

rf-induced adiabatic potentials

Dressing the atoms

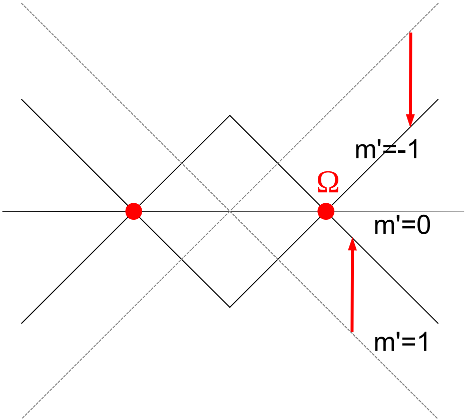
Spin states in a quadrupole field coupled through a rf field...



rf-induced adiabatic potentials

Dressing the atoms

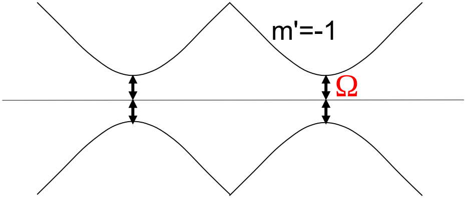
...in the dressed states basis...



rf-induced adiabatic potentials

rf-induced adiabatic potentials

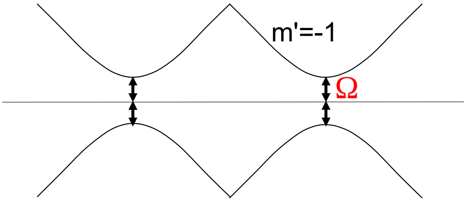
...trap minima at the resonant points = isomagnetic surface.



rf-induced adiabatic potentials

rf-induced adiabatic potentials

isomagnetic surfaces: ellipsoids with $r_0 \propto \frac{\omega_{\text{rf}}}{b'}$



$$\omega_z \propto \frac{b'}{\sqrt{\Omega}} \sim \text{1-2 kHz} \qquad \omega_x, \omega_y \propto \sqrt{\frac{g}{r_0}} \sim \text{20-50 Hz}$$

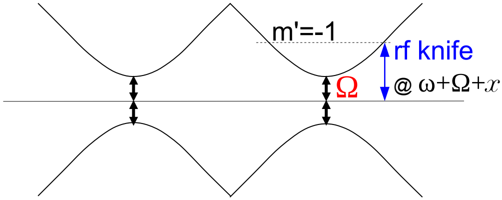
anisotropy $\eta = \frac{\omega_x}{\omega_y}$ controlled through rf polarization

NB: $\eta = 1$ with a circular rf polarization

rf-induced adiabatic potentials

rf-induced adiabatic potentials

isomagnetic surfaces: ellipsoids with $r_0 \propto \frac{\omega_{\text{rf}}}{b'}$

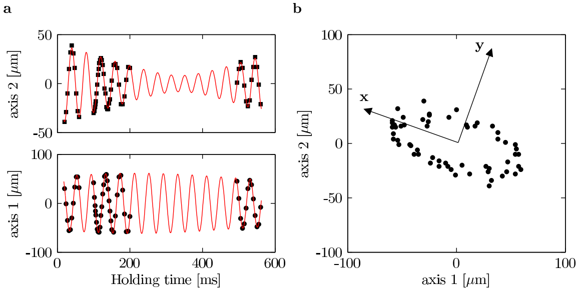


$$\omega_z \propto \frac{b'}{\sqrt{\Omega}} \sim \text{1-2 kHz} \qquad \omega_x, \omega_y \propto \sqrt{\frac{g}{r_0}} \sim \text{20-50 Hz}$$

temperature T controlled with a rf knife at $\omega_{\text{rf}} + \Omega + \nu_{\text{cut}}$

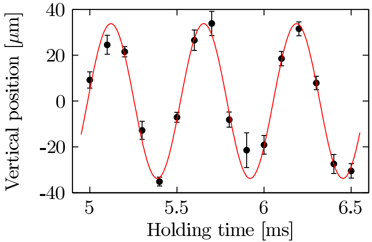
Confining a gas to two dimensions
A very smooth trap for a 2D quantum gas

- check the 2D character with time-of-flight expansions
- interaction strength: $\tilde{g} \sim 0.1 \Rightarrow$ weak interactions
- 2D criteria:
  - interaction energy: $\alpha = \dfrac{\mu_{2D}}{\hbar\omega_z} = 0.1 \cdots 0.3 < 1 \Rightarrow$ well in 2D
  - thermal energy $k_B T \sim \hbar\omega_z$; low thermal excitation
- Very smooth harmonic trap: no damping of the dipole modes



Confining a gas to two dimensions
Expansion of a 2D gas

dipole oscillations along z

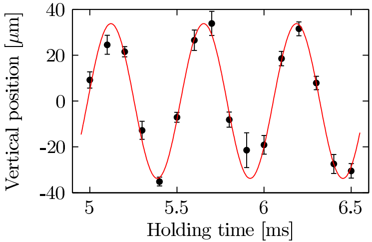


vertical frequency $\nu_z = 1.9\,\mathrm{kHz}$

Confining a gas to two dimensions

Expansion of a 2D gas

dipole oscillations along z

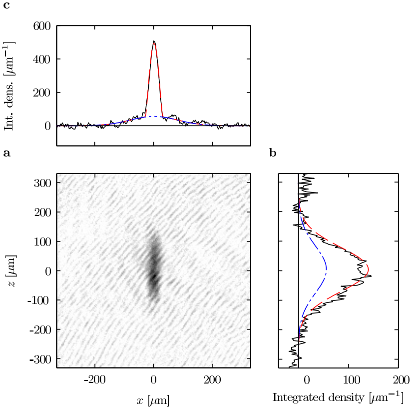


vertical frequency $\nu_z = 1.9\,\text{kHz}$

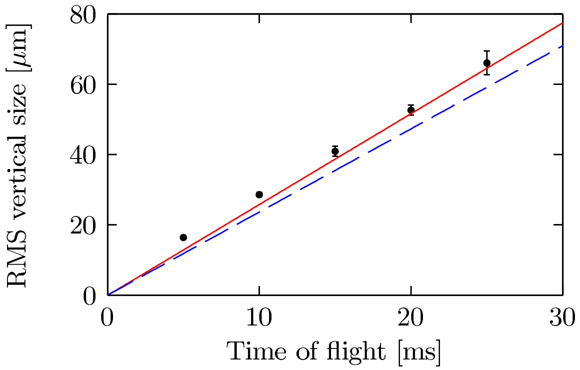
25 ms time-of-flight $\longrightarrow$

small thermal fraction

anisotropic expansion of a 2D gas



Confining a gas to two dimensions
Expansion of a 2D gas



- experimental data

— — theory: ground state expansion for an ideal gas at ν_z...

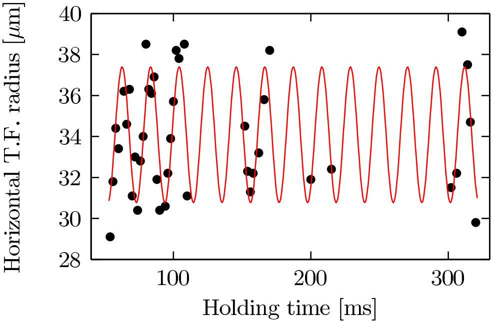
—— ...or for an interacting 2D gas [Foot 2010]

Observation of the monopole mode

Isotropic trap

Circular rf polarization ⇒ isotropic 2D trap
Excitation through a sudden change in ω
Very low T (no thermal fraction)

• experimental data
—— sinusoidal fit
[Merloti NJP2013]



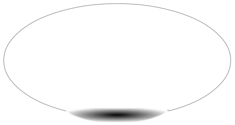
typical data: Ω_M close to 2ω; no measurable damping

Adiabatic potentials

Illustrations of Lecture 3: ring trap / TAAP traps

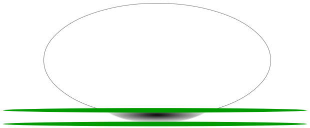
Ring
Ring trap for dressed atoms

bubble trap (dressed quadrupole) + dipole trap (standing wave or double light sheet)

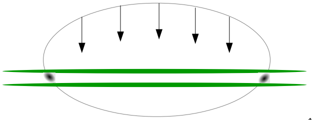


Morizot et al., PRA **74** 023617, 2006

Heathcote et al., New J. Phys. **10** 043012 (2008)

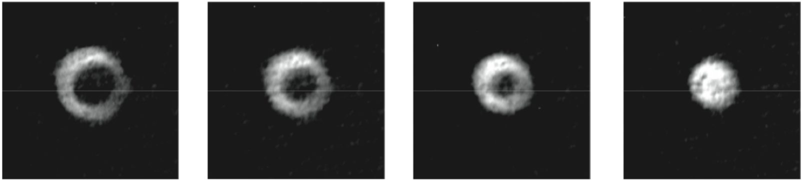


trap loading with a bias field



Ring

Ring trap for dressed atoms



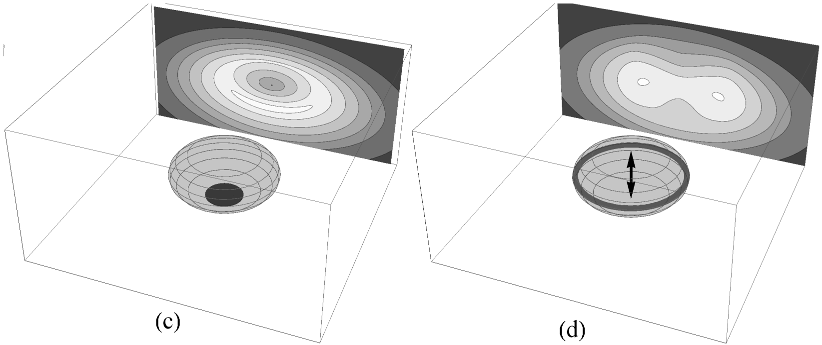
(a) $B_0^{DC} = 1.0$ G (b) $B_0^{DC} = 1.1$ G (c) $B_0^{DC} = 1.2$ G (d) $B_0^{DC} = 1.3$ G

Atoms in a ring (Oxford group)

Heathcote et al., New J. Phys. **10** 043012 (2008)

TAAP ring

Time-average adiabatic potential



Add a vertical homogeneous magnetic field, modulated in time.

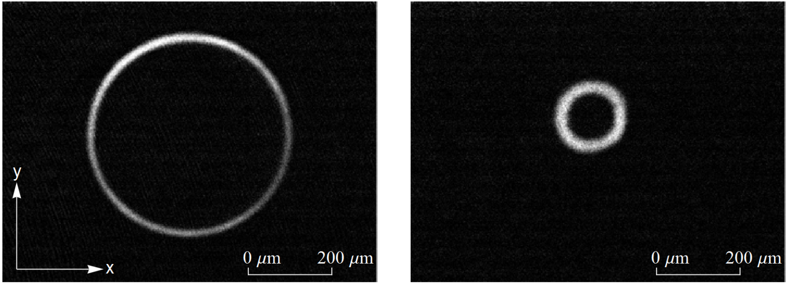
$\omega_{\text{osc}} \ll \omega_{\text{mod}} \ll \Omega_+ \ll \omega$

100 Hz < 7 kHz < 50 kHz < 1.4 MHz

TAAP ring

Time-average adiabatic potential

Results



a) b)

Proposal: Lesanovsky and von Klizting, PRL 2007.
Experiment: Sherlock et al., PRA 2011 (Oxford group)