Lecture 2: Adiabatic potentials

Hélène Perrin

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

Vortex Dynamics, Turbulence and Related Phenomena in Quantum Fluids — Natal, June 24-28, 2019

Outline of the course

- Lecture 1: Bose-Einstein condensation, superfluid hydrodynamics and collective modes
- Lecture 2: Adiabatic potentials for confining quantum gases
- Lecture 3: Superfluid dynamics at the bottom of a bubble trap

Tuning quantum gases

Quantum gases benefit from a wide range of tunable parameters:

- temperature in the range 10 nK – 1 μK
- interaction strength: scattering length a
- dynamical control of the confinement geometry
- periodic potentials (optical lattices)
- low dimensional systems accessible (1D, 2D)
- several internal states or species available
- easy optical detection

Using adiabatic potentials

This lecture: what adiabatic potentials are useful for:

- temperature in the range 10 nK – 1 μK
- interaction strength: scattering length a
- dynamical control of the confinement geometry
- periodic potentials (optical lattices)
- low dimensional systems accessible (1D, 2D)
- several internal states or species available
- easy optical detection

Using adiabatic potentials

This lecture: what adiabatic potentials are useful for:

- support temperature in the range 10 nK – 1 μK
- interaction strength controlled by confinement
- dynamical control of the confinement geometry
- periodic potentials (rf lattices)
- low dimensional systems accessible (1D, 2D)
- several internal states or species available
- easy optical detection

Outline of the course

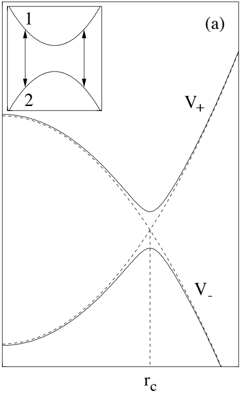
1. Principle of adiabatic potentials
   - Atom-field interaction
   - Magnetic traps
   - Coupling magnetic states with an rf field
   - Trapping surface
2. Examples of adiabatic potentials
   - First historical example: microwave dressing
   - Dressed Ioffe-Pritchard trap
   - Dressed quadrupole trap
   - Dressing with multiple frequencies
3. Probing adiabatic potentials
   - Dressed picture
   - Rf spectroscopy of the dressed states
   - Fulfilling the criterion for adiabaticity

References for the lecture

1. Detailed theory of the rf-based adiabatic potentials:
   H. Perrin and B. Garraway,
   Trapping atoms with radio-frequency adiabatic potentials,
   in Ennio Arimondo, Chun C. Lin, Susanne F. Yelin, editors:
   Advances In Atomic, Molecular, and Optical Physics **66**
   AAMOP, UK: Academic Press, pp. 181-262 (2017); see also
   arXiv:1706.08063
2. Review on recent applications of rf-based adiabatic potentials:
   B. M. Garraway and H. Perrin,
   Recent developments in trapping and manipulation of atoms with adiabatic potentials,
   Topical Review in J. Phys. B **49**, 172001 (2016).

Principle of adiabatic potentials

Principle of adiabatic potentials



[Zobay & Garraway (PRL 2001)]

Principle of adiabatic potentials

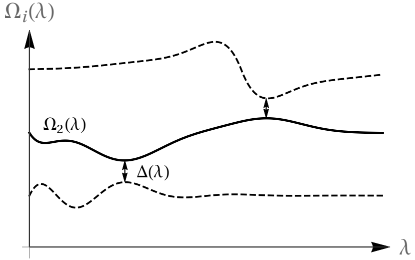
General idea:

- Eigenstates $|\psi(\lambda)\rangle$ and eigenenergies $\hbar\Omega(\lambda)$ and splitting $\hbar\Delta(\lambda)$ depend from an external parameter λ (here: magnetic field and rf field)
- Variations of this parameter λ with position or time
- For slow enough variations, the atomic states follows adiabatically the local eigenstate $|\psi(\lambda)\rangle$

Condition:

$$\dot{\lambda}\langle\psi|\frac{\partial|\psi\rangle}{\partial\lambda} \ll \Delta(\lambda)$$

or $\dot{x}\dfrac{\partial\lambda}{\partial x}\langle\psi|\dfrac{\partial|\psi\rangle}{\partial\lambda} \ll \Delta(\lambda)$



Here: $|\psi\rangle$ is a magnetic state dressed by radiofrequency photons

Interaction between an atom and a magnetic field

Reminder on spin operators

Eigenstates of the total angular momentum operator $\hat{\mathbf{F}}$:

Given an axis z, $\hat{\mathbf{F}}^2$ and $\hat{F}_z = \hat{\mathbf{F}} \cdot \mathbf{e}_z$ can be diagonalized in the same basis $\{|m\rangle_z\}$, with eigenvalues:

$$\hat{\mathbf{F}}^2|m\rangle_z = F(F+1)\hbar^2|m\rangle_z \qquad \hat{F}_z|m\rangle_z = m\hbar|m\rangle_z$$

The whole basis is built using the $\hat{F}_\pm = \hat{F}_x \pm i\hat{F}_y$ operators:

$$\hat{F}_\pm|m\rangle_z = \hbar\sqrt{F(F+1) - m(m\pm 1)}|m\pm 1\rangle_z$$

Remark: $\hat{F}_x = \frac{1}{2}\left(\hat{F}_+ + \hat{F}_-\right)$.

Interaction between an atom and a magnetic field

Interaction hamiltonian

Zeeman effect: The interaction between an atom with total angular momentum $\hat{\mathbf{F}}$ and a magnetic field $\mathbf{B}_0 = B_0\mathbf{u}$ writes

$$\hat{H} = -\gamma\hat{\mathbf{F}}\cdot\mathbf{B}_0 = \frac{g_F\mu_B}{\hbar}B_0\hat{F}_{\mathbf{u}} = \omega_0\hat{F}_{\mathbf{u}},$$

where $\gamma = -\dfrac{g_F\mu_B}{\hbar}$ is the gyromagnetic ratio, g_F is the Landé factor and μ_B is the Bohr magneton. ω_0 is the Larmor frequency.

The eigenstates of $\hat{H}$ are the states $|m\rangle_{\mathbf{u}}$, eigenstates of $\hat{F}_{\mathbf{u}} = \hat{\mathbf{F}}\cdot\mathbf{u}$. If the z axis is chosen along $\mathbf{u}$, these states are $|m\rangle_z$. The corresponding eigenenergies are

$$E_m = mg_F\mu_B B_0 = m\hbar\omega_0.$$

Magnetic trapping

Position dependent magnetic field

Now $\mathbf{B}_0$ depends on position, in modulus B_0 and direction $\mathbf{u}$: $\mathbf{B}_0(\mathbf{r}) = B_0(\mathbf{r})\mathbf{u}(\mathbf{r})$.

If the atomic motion is slow enough, the atoms follow adiabatically the *local* magnetic eigenstate $|m\rangle_{\mathbf{u}(\mathbf{r})}$.

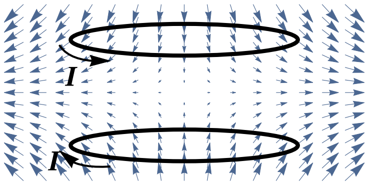
The local energy $E_m(\mathbf{r})$ acts as a trapping potential:

$$V_m(\mathbf{r}) = g_F \mu_B B_0(\mathbf{r})$$

Low field-seekers are trapped at a magnetic field minimum.

Example of magnetic traps
Quadrupole trap

Two coils with opposite currents: a quadrupole trap.



Field produced: $\mathbf{B}_0(\mathbf{r}) = b' \left(x\mathbf{e}_x + y\mathbf{e}_y - 2z\mathbf{e}_z \right)$

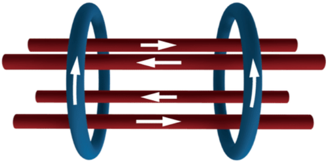
Potential: we define $\alpha = g_F \mu_B b'/\hbar$

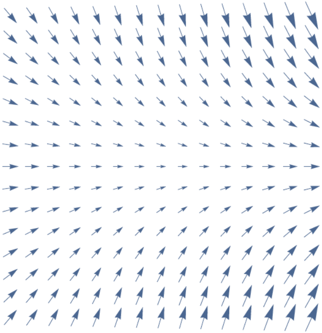
$$B_0(\mathbf{r}) = b' \sqrt{x^2 + y^2 + 4z^2} \Rightarrow V_m(\mathbf{r}) = \hbar\alpha \sqrt{x^2 + y^2 + 4z^2}$$

Minimum with zero field at the center $(0, 0, 0)$

Example of magnetic traps
Ioffe-Pritchard trap

4 bars: 2D quadrupole + 2 pinch coils with the same current: a Ioffe-Pritchard trap.





Field produced: $\mathbf{B}_0(\mathbf{r}) \simeq \left(B_0 + \frac{b''}{2}x^2\right)\mathbf{e}_x + b'\left(y\mathbf{e}_y - z\mathbf{e}_z\right)$

Potential: $V_m(\mathbf{r}) \simeq \hbar\Omega_0 + \frac{1}{2}\omega_x^2 x^2 + \frac{1}{2}\omega_\perp^2(y^2+z^2)$

Minimum with non-zero field B_0 at the center $(0,0,0)$

Rf coupling between magnetic states

Static + oscillating magnetic fields

Two fields: static $\mathbf{B}_0 = B_0 \mathbf{e}_z$ and oscillating $\mathbf{B}_1 = B_1 \cos(\omega t)\,\mathbf{e}_x$.
Hamiltonian:

$$\hat{H} = -\gamma \hat{\mathbf{F}} \cdot (\mathbf{B}_0 + \mathbf{B}_1(t)) = \omega_0 \hat{F}_z + \Omega_1 \cos(\omega t) \hat{F}_x,$$

where Ω_1 is the Rabi frequency of the rf field. Using $\hat{F}_\pm$:

$$\hat{H} = \omega_0 \hat{F}_z + \left\{ \frac{\Omega_+}{2}\, e^{-i\omega t} \hat{F}_+ + \text{h.c.} \right\} + \left\{ \frac{\Omega_-}{2}\, e^{-i\omega t} \hat{F}_- + \text{h.c.} \right\},$$

with $\Omega_+ = \Omega_1/2$ weight on the σ^+ polarization ($\Omega_- = \Omega_1/2$ weight on the σ^-). Hamiltonian in the rotating frame (rotating at ω around $\mathbf{B}_0$) within rotating wave approximation (RWA):

$$\hat{H}' = -\delta \hat{F}_z + \Omega_+ \hat{F}_x$$

with $\delta = \omega - \omega_0$, detuning from magnetic resonance.

Adiabatic potential
Eigenstates and energies

$$\hat{H}' = -\delta \hat{F}_z + \Omega_+ \hat{F}_x = \sqrt{\delta^2 + \Omega_+^2}\, \hat{\mathbf{F}} \cdot \mathbf{u}_\theta$$

with $\mathbf{u}_\theta = \cos\theta \mathbf{e}_z + \sin\theta \mathbf{e}_x$ and

$$\cos\theta = \frac{-\delta}{\sqrt{\delta^2 + \Omega_+^2}}, \qquad \sin\theta = \frac{\Omega_+}{\sqrt{\delta^2 + \Omega_+^2}}.$$

Eigenstates: $|m\rangle_\theta \equiv |m\rangle_{\mathbf{u}_\theta}$. Eigenenergies: $m\hbar\sqrt{\delta^2 + \Omega_+^2}$.

For position dependent B_0 and/or B_1, i.e. $\omega_0(\mathbf{r})$ and/or $\Omega_+(\mathbf{r})$, rf-dressed adiabatic potentials:

$$V_m(\mathbf{r}) = m\hbar\sqrt{\delta^2(\mathbf{r}) + \Omega_+^2(\mathbf{r})}\,.$$

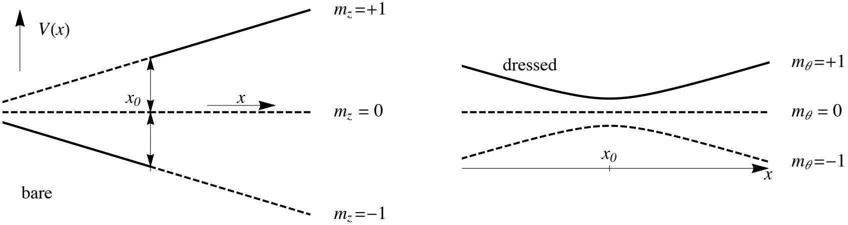
Adiabatic potential for a linear magnetic field

Eigenstates and energies

For a linear static magnetic field: $B_0(x) = b'x$, with uniform Ω_+

$$V_m(x) = m\hbar\sqrt{\alpha^2(x-x_0)^2 + \Omega_+^2}$$

where $\alpha = g_F\mu_B b'/\hbar$ and $x_0 = \omega/\alpha$.
Ex: $F = 1$, bare basis vs dressed basis

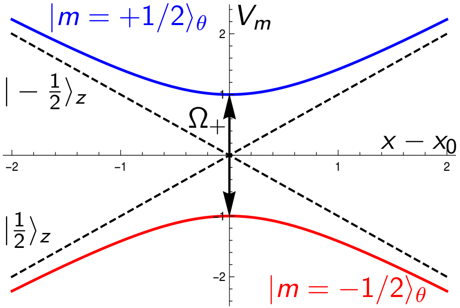


[Figure from Perrin & Garraway, Adv. At. Mol. Opt. Phys. 2017]

Adiabatic potential for a linear magnetic field
Oscillation frequency

Ex: $F = 1/2$: avoided crossing between dressed states

Close to the trap minimum at $x = x_0$:



$$V_m(x) = m\hbar\sqrt{\alpha^2(x-x_0)^2 + \Omega_+^2} \underset{x\sim x_0}{\simeq} m\hbar\Omega_+ + \frac{1}{2}M\omega_{\text{trap}}^2 x^2$$

where $$\omega_{\text{trap}} = \alpha\sqrt{\frac{m\hbar}{M\Omega_+}} \propto \frac{b'}{\sqrt{\Omega_+}}$$

high trap frequency for large magnetic gradients and low rf coupling.

Typical shape for adiabatic traps

Trapping surface

Adiabatic potential:

$$V_m(\mathbf{r}) = m\hbar\sqrt{\delta^2(\mathbf{r}) + \Omega_+^2(\mathbf{r})}$$

- The detuning $\delta(\mathbf{r}) = \omega - \omega_0(\mathbf{r})$ varies quickly (like the magnetic potential)
- The rf coupling $\Omega_+(\mathbf{r})$ varies slowly, especially if Ω_1 is uniform $\Rightarrow$ variations dues to the respective orientations of $\mathbf{B}_0$ and $\mathbf{B}_1$.
- To a good approximation: the trap minimum lies within the isomagnetic surface $\delta(\mathbf{r}) = 0$ (resonant surface $\omega_0(\mathbf{r}) = \omega$)
- Within this surface, $V_m(\mathbf{r}) = m\hbar\Omega_+(\mathbf{r})$ and the minimum occurs where Ω_+ is minimum or at the bottom where gravity attracts the atoms.

Principle of rf-induced adiabatic potentials

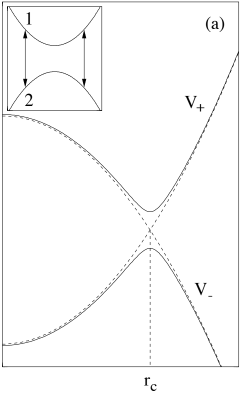
Trapping to an isomagnetic surface

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):

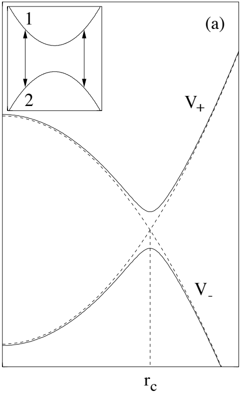
$$\mathbf{B}_0(\mathbf{r}) + \mathbf{B}_1 \cos \omega t$$

inhomogeneous magnetic field + rf field

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

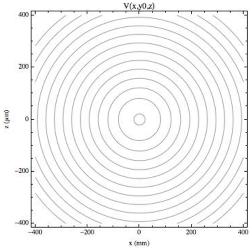
atoms trapped at the isomagnetic surface of an inhomogeneous magnetic field set by ω:

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



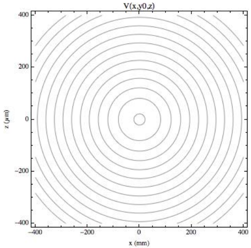
Trapping to an isomagnetic surface
Bubbles and double wells

magnetic landscape: iso-B surfaces

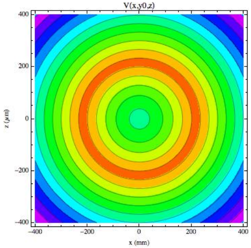


Trapping to an isomagnetic surface
Bubbles and double wells

magnetic landscape: iso-B surfaces

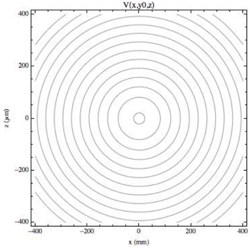


$\mathbf{B}_1$ rf on selecting the iso-B surface

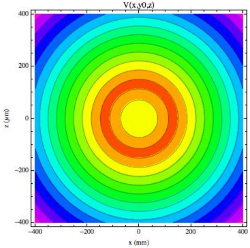


Trapping to an isomagnetic surface
Bubbles and double wells

magnetic landscape: iso-B surfaces



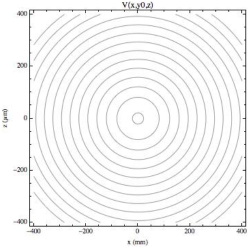
$\mathbf{B}_1$ rf on selecting the iso-B surface

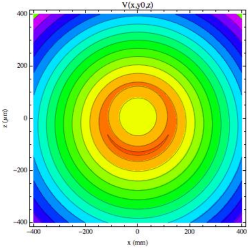


Trapping to an isomagnetic surface

Bubbles and double wells

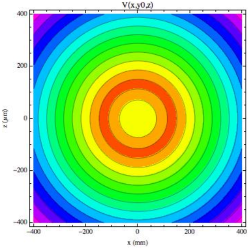
magnetic landscape: iso-B surfaces





gravity on: flat trap

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

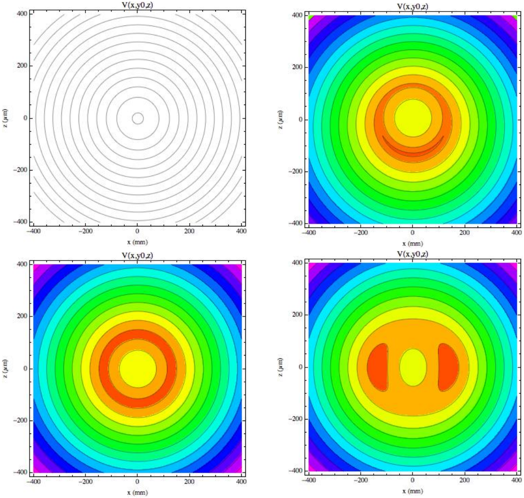


Trapping to an isomagnetic surface

Bubbles and double wells

magnetic landscape: iso-B surfaces

gravity on: flat trap

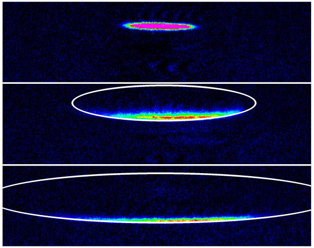


$\mathbf{B}_1$ rf on selecting the iso-B surface

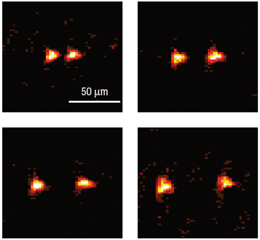
inhomogeneous rf coupling $\mathbf{B}_1(\mathbf{r})$: double well

Examples of adiabatic potentials

Nice examples of adiabatic potentials



[Colombe et al. (2004)]



[Schumm et al. (2005)]

Early history 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 $\approx 4\ \mu$K. 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.

Early history 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

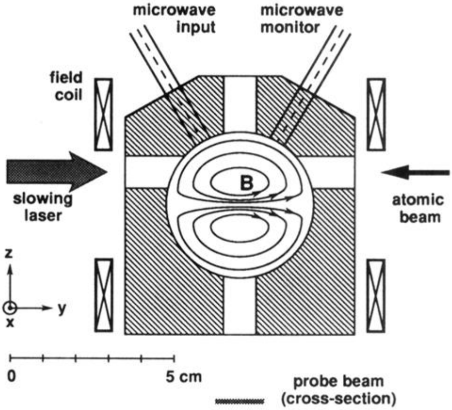
$$U(\mathbf{r}) = -\bar{\mu}B(\mathbf{r}) - \tfrac{1}{2}\hbar\,\Omega(\mathbf{r}) + mgz\ ,$$

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 $\delta(\mathbf{r}) = 2\mu_z[B_{\rm res} - B(\mathbf{r})]/\hbar$, 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 $\delta(\mathbf{r}) = \omega_{\rm mw} - \mu B(\mathbf{r})/\hbar$.

Early history of adiabatic potentials
Trapping with a microwave

[Spreeuw 1994]



Early history of adiabatic potentials
Trapping with a microwave

[Spreeuw 1994]

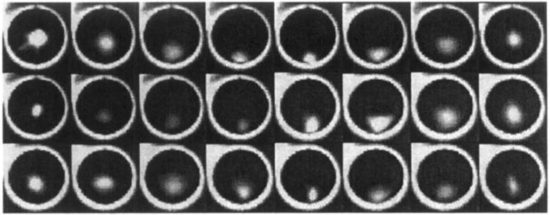


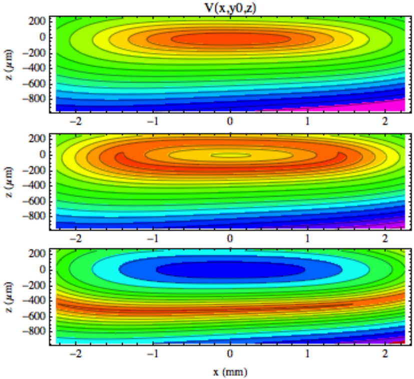
FIG. 3. Sequence of images with 67 ms successive increase in trapping time. The bright ring is a 1 cm diameter observation hole in the side of the cavity. For this sequence the microwave power level was 42 W.

Cs atoms oscillating in the microwave + magnetic field trap

Example 1: The dressed Ioffe-Pritchard trap

First experimental realization

A “bubble trap” in the presence of gravity

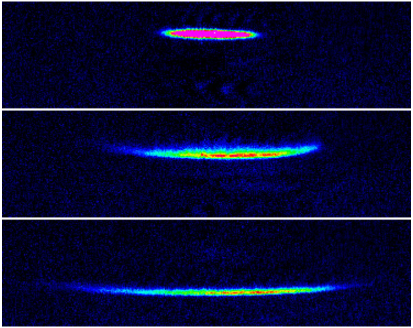


calculated isopotential lines

no rf

ω_1

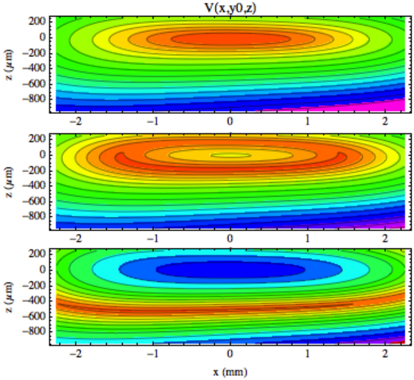
ω_2



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

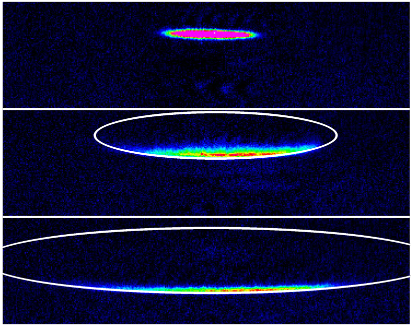


calculated isopotential lines

no rf

ω_1

ω_2

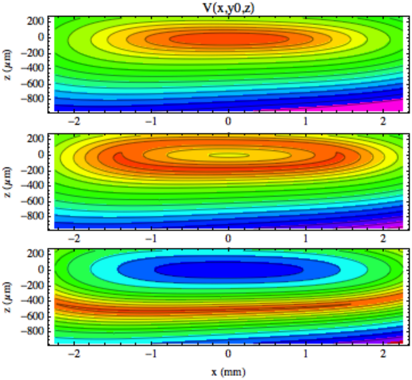


experiment: Colombe et al., EPL **67**, 593 (2004)

Example 1: The dressed Ioffe-Pritchard trap

First experimental realization

Seing the bubble structure

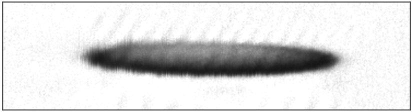


no rf

ω_1

ω_2

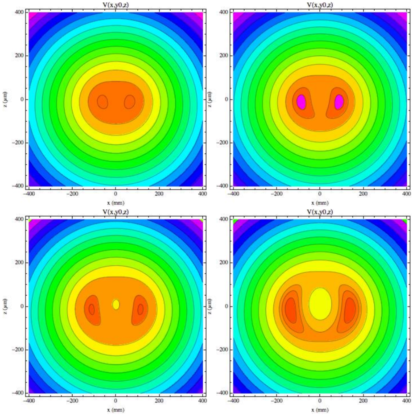
calculated isopotential lines

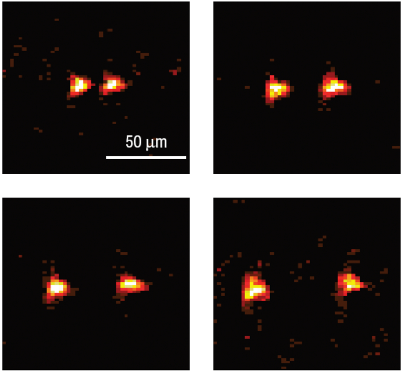


at larger temperature

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

With an inhomogeneous rf coupling: double well potential





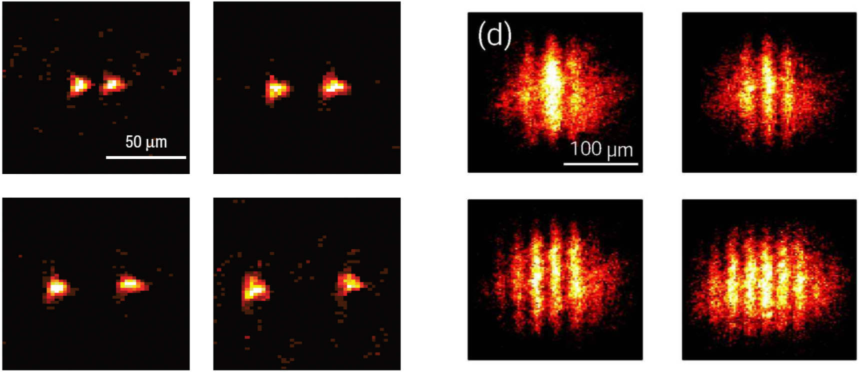
[Schumm et al., Nat. Phys. 2005]

Well separation adjusted with the rf frequency.

A double well potential on an atom chip

Atom interferometry

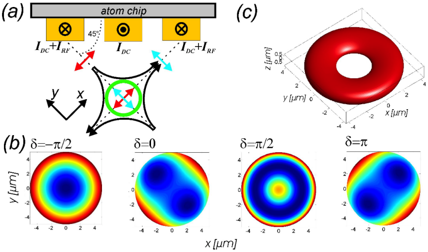
Interference fringes from atoms released from the double well potential



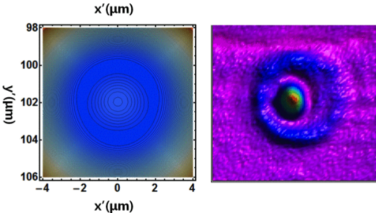
[Schumm et al., Nat. Phys. 2005]

A ring trap
Playing with rf polarization

With a circular rf polarization: annular potential



Proposal: [Lesanovsky et al., PRA 2006]



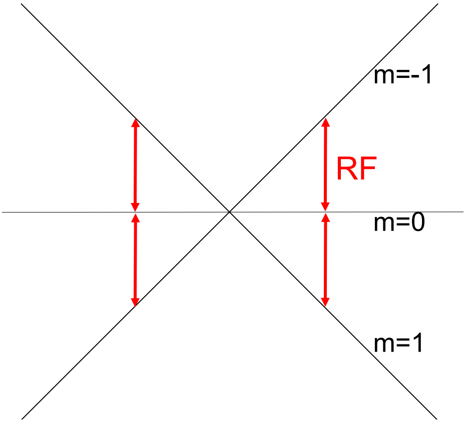
Experiment: [Kim et al., PRA 2016]

Example 2: The dressed quadrupole trap

Dressing the spin states

- $\mathbf{B}_0 = b'(x\mathbf{e}_x + y\mathbf{e}_y - 2z\mathbf{e}_z)$

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

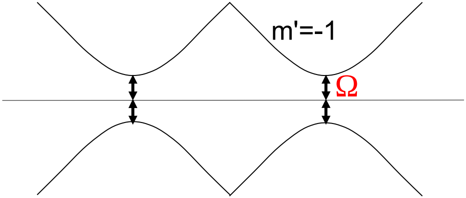


Example 2: The dressed quadrupole trap

Dressing the spin states

- $\mathbf{B}_0 = b'(x\mathbf{e}_x + y\mathbf{e}_y - 2z\mathbf{e}_z)$

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



isomagnetic surfaces: ellipsoids with $r_0 \propto \dfrac{\omega}{b'}$

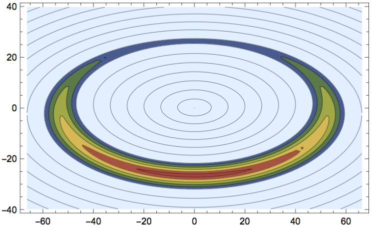
Example 2: The dressed quadrupole trap

From the bubble to the ring

$$\omega_z \propto \frac{b'}{\sqrt{\Omega}} \sim \text{1-2 kHz}$$

$$\omega_x, \omega_y \propto \sqrt{\frac{g}{r_0}} \sim \text{20-50 Hz}$$

side view (isopotentials):



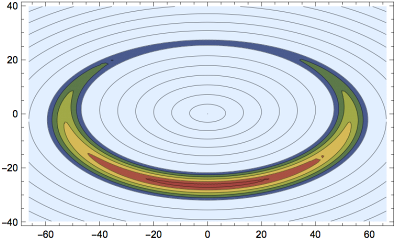
- very flat $\omega_z \gg \omega_{x,y}$
- $\eta = \dfrac{\omega_x}{\omega_y}$ controlled through rf polarization:
- rotationally invariant ($\eta = 1$) for a σ^+ polarization along z
- anisotropic ($\eta \neq 1$) for linear horizontal polarization
- geometry can be modified dynamically
- ideal for the study of collective modes of the 2D trapped gas

Example 2: The dressed quadrupole trap

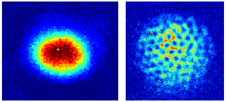
From the bubble to the ring

- $\mathbf{B}_0 = b'(x\mathbf{e}_x + y\mathbf{e}_y - 2z\mathbf{e}_z)$
- rotationally invariant for a σ^+ polarization along z
- anisotropic for linear horizontal polarization
- geometry can be modified dynamically
- ideal for the study of collective modes of the 2D trapped gas

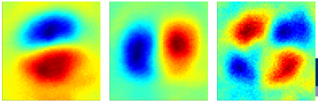
side view (isopotentials):



top-view:
a [2D] quantum gas



collective modes:



Ring trap from the dressed quadrupole

Ring trap for dressed atoms

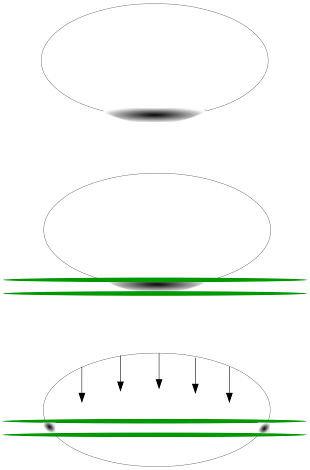
bubble trap (dressed quadrupole) + dipole trap (standing wave or double light sheet)

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

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

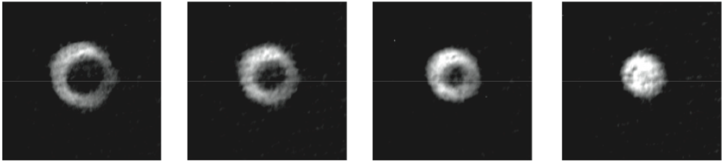
De Goër et al. (2018)

trap loading with a bias field



Ring trap from the dressed quadrupole
Ring trap for dressed atoms

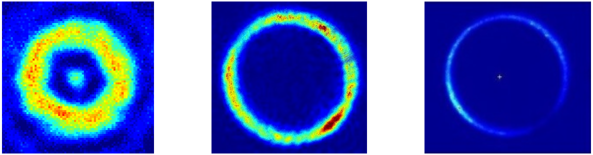
Atoms in a ring (Oxford group)



(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

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

Atoms in a ring (LPL group)

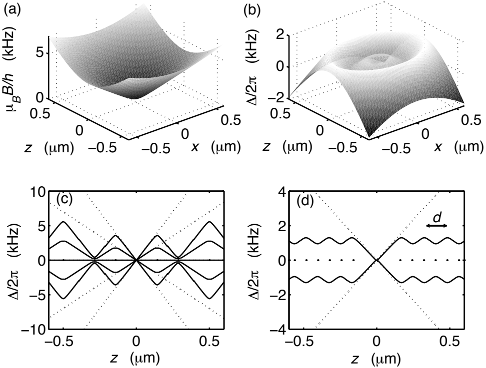


$r_0 = 20\ \mu$m 100 μm 125 μm

Example 3: Multiple rf frequencies

A rf lattice

Select several iso-B surfaces with multiple rf frequencies

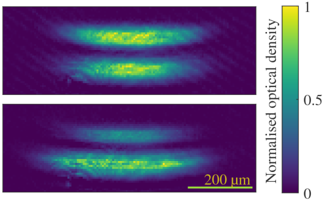


Proposal: [Courteille et al., J. Phys. B 2006]

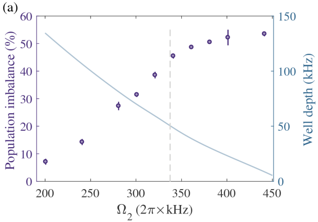
Example 3: Multiple rf frequencies

Realization with 3 frequencies and gravity: double-well

3 frequencies and gravity in the dressed quadrupole trap



double well with 3 rf



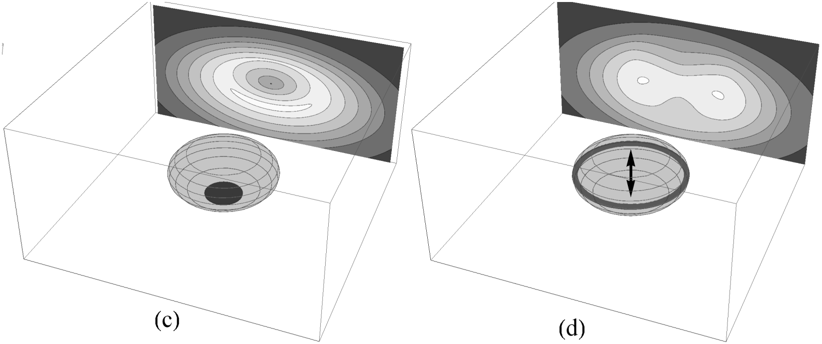
population imbalance vs Ω_2

Harte et al., Phys. Rev. A **97**, 013616 (2018)

Multiple frequencies: Time-average adiabatic potential

TAAP ring

Starting from a dressed quadrupole trap:



Add a vertical homogeneous magnetic field, modulated in time.

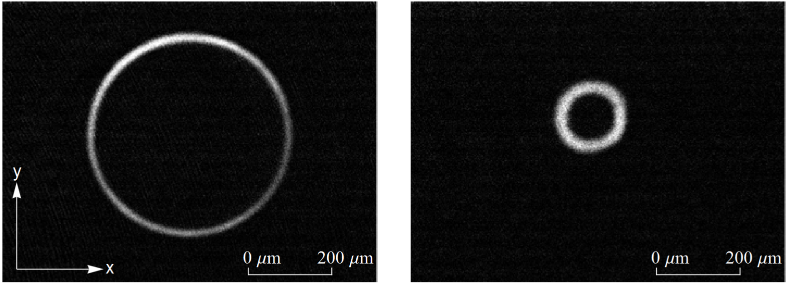
$\omega_{\mathrm{osc}} \ll \omega_{\mathrm{mod}} \ll \Omega_{+} \ll \omega$

100 Hz $<$ 7 kHz $<$ 50 kHz $<$ 1.4 MHz

TAAP ring

Time-average adiabatic potential

Results

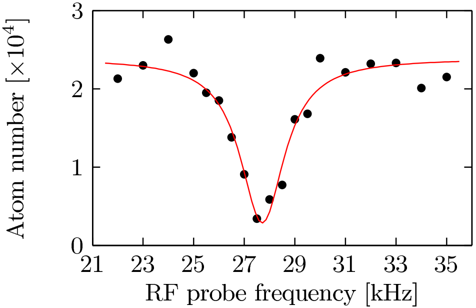


a) b)

Proposal: Lesanovsky and von Klizting, PRL 2007.
Experiments: Sherlock et al., PRA 2011 (Oxford group)
Navez et al., NJP 2016 (von Klitzing group)

Probing adiabatic potentials

Probing adiabatic potentials



[Merloti et al. (NJP 2013)]

Dressed picture

Description with a quantized rf field

Write the Hamiltonian using a quantum rf field:

$$\hat{\mathbf{B}}_1 = (b_+ \, \mathbf{e}_+ + b_- \, \mathbf{e}_-) \; a + h.c.$$

Spin + field Hamiltonian in the limit of large photon number N:

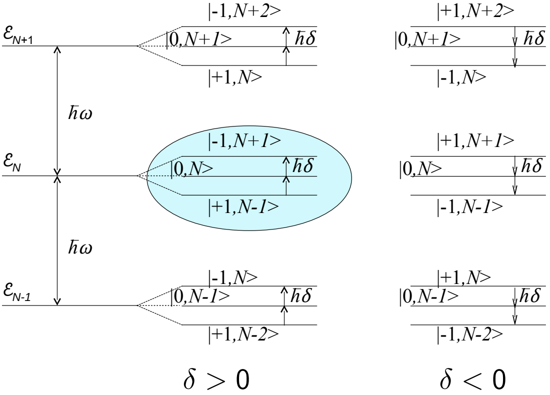
$$\hat{H} = \omega_0 \hat{F}_z + \hbar\omega a^\dagger a + \left[\frac{\Omega_+}{2\sqrt{\langle N \rangle}} \left(a \, \hat{F}_+ + a^\dagger \, \hat{F}_- \right) + \frac{\Omega_-}{2\sqrt{\langle N \rangle}} \left(a \, \hat{F}_- + a^\dagger \, \hat{F}_+ \right) \right]$$

Uncoupled states:

$|m, N\rangle$ with energy $E_{m,N} = m\hbar\omega_0 + N\hbar\omega = -m\hbar\delta + (N+m)\hbar\omega.$

Dressed manifolds
Energy of uncoupled states

Uncoupled states: $E_{m,N} = -m\hbar\delta + (N+m)\hbar\omega$
Within RWA: $|\delta| \ll \omega \Rightarrow$ well separated manifolds (here $F = 1$)



Dressed manifolds

Coupling between states

Coupling: 2 terms

- inside a given manifold: $\frac{\Omega_+}{2\sqrt{\langle N\rangle}}\left(a\,\hat{F}_+ + a^\dagger\,\hat{F}_-\right)$
- between manifolds separated by $2\hbar\omega$: $\frac{\Omega_-}{2\sqrt{\langle N\rangle}}\left(a\,\hat{F}_- + a^\dagger\,\hat{F}_+\right)$

$\Rightarrow$ only keep the first term within RWA

$$\langle m \mp 1, N \pm 1|\hat{V}_c|m, N\rangle \simeq \frac{\Omega_+}{2}$$

Dressed manifolds
Coupling between states

Uncoupled states:

$$E_{m,N} = -m\hbar\delta + (N+m)\hbar\omega$$

Coupling amplitude:

inside a given manifold:

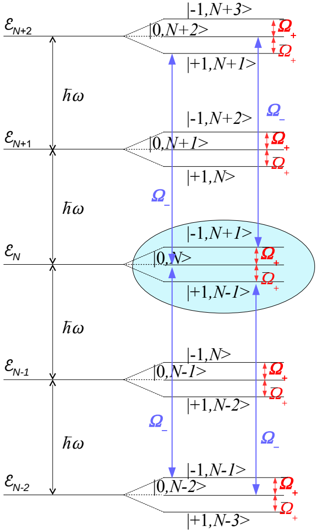
$$\frac{\Omega_+}{2\sqrt{\langle N\rangle}}\left(a\,\hat{F}_+ + a^\dagger\,\hat{F}_-\right)$$

between manifolds split by $2\hbar\omega$:

$$\frac{\Omega_-}{2\sqrt{\langle N\rangle}}\left(a\,\hat{F}_- + a^\dagger\,\hat{F}_+\right)$$

$\Rightarrow$ only keep the first (resonant) term within RWA

$$\langle m\mp 1, N\pm 1|\hat{V}_c|m,N\rangle \simeq \frac{\Omega_+}{2}$$

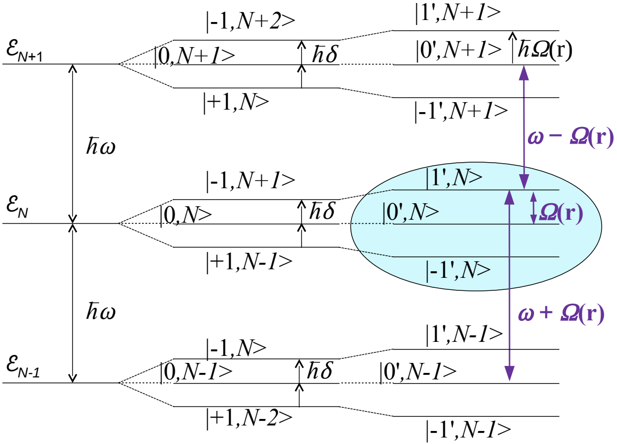


Rf spectroscopy

Coupling between dressed states with a weak rf probe

We define the local splitting by $\Omega(\mathbf{r}) = \sqrt{\delta^2(\mathbf{r}) + \Omega_+^2(\mathbf{r})}$.

Dressed energies: $m\hbar\Omega(\mathbf{r}) + N\hbar\omega \Rightarrow$ transitions at Ω, $\omega \pm \Omega$

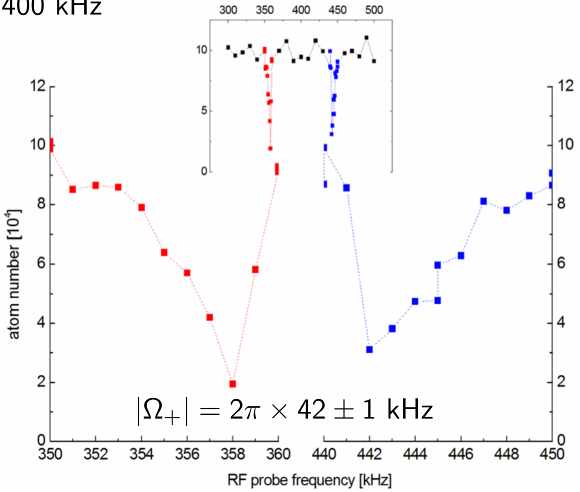


Rf spectroscopy

Spectroscopy of an ultracold gas in a dressed quadrupole trap

At the trap bottom ($\delta = 0$), two peaks at $\omega_{\text{probe}} = \omega \pm |\Omega_+|$

$\omega = 2\pi \times 400$ kHz

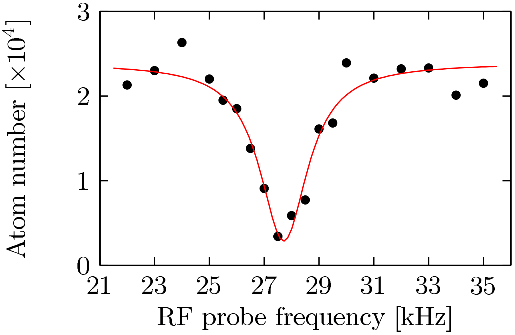


$|\Omega_+| = 2\pi \times 42 \pm 1$ kHz

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

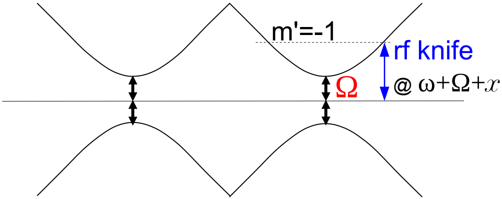


Merloti et al., NJP **15**, 033007 (2013)

Application to rf evaporative cooling

Back to the dressed quadrupole trap

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



temperature T controlled with a rf knife (weak second rf field) at $\Omega + \nu_{\text{cut}}$ or $\omega + \Omega + \nu_{\text{cut}}$

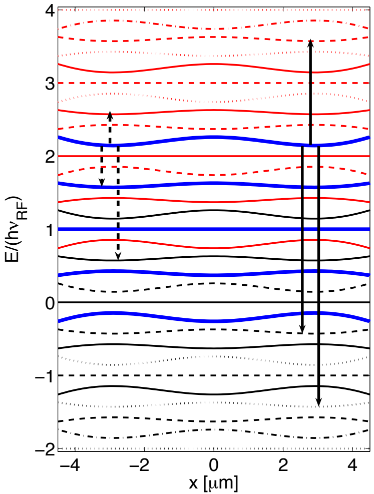
Beyond RWA

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]

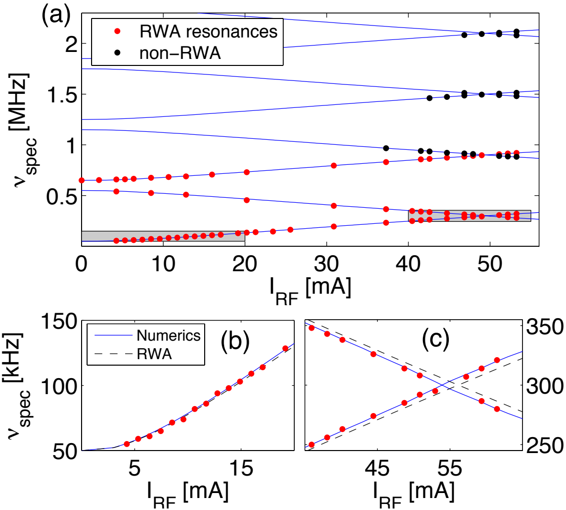


Beyond RWA

Spectroscopy in an atom chip adiabatic potential

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

Shift from RWA predictions.

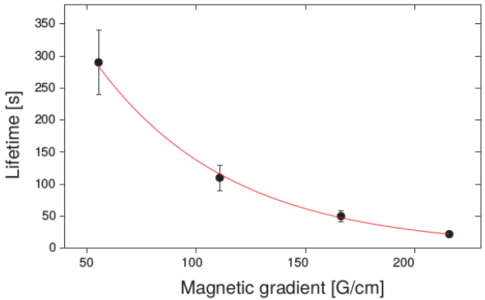


Landau-Zener losses

Criterion for adiabaticity

Landau-Zener theory: atoms will leave the adiabatic state if the state variations are faster than Ω: for large b'/low Ω

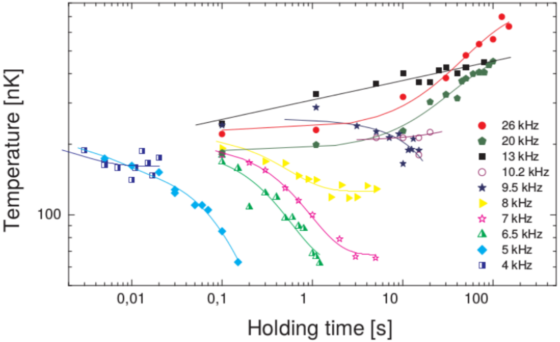
- quiet DDS source is necessary
- avoid rf phase noise, frequency noise, amplitude noise
- lifetime depends exponentially on b', Ω and velocity



Landau-Zener losses
Criterion for adiabaticity

Landau-Zener theory: atoms will leave the adiabatic state if the state variations are faster than Ω: for large b'/low Ω

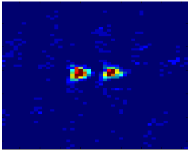
- lifetime depends exponentially on b', Ω and velocity
- evaporation induced by energy-dependent LZ losses



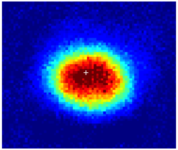
Summary

Adiabatic potentials: A new tool for manipulating ultracold atoms or quantum gases

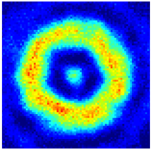
- Double-wells,. . .



- . . . 2D gases,. . .



- . . . ring traps,. . .



- . . . and more!