Microchips Meet Atomic Gases
– Cold Dilute Gases in the Vicinity of Microstructures –
„BEC on a chip“

M³, March 23rd, 2009
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Outline

- Introduction
- General atom physics
  - Lasercooling and MOTs
  - opto-atomic set-ups
  - conventional BEC
- Micropotentials
- Detailed examples
  - BEC on a microchip
  - quantum information in microtraps: coherence
  - BEC and gravity
  - BEC coupled to nanomechanical resonators
  - Matter-wave interference
- Final words
Introduction: History

- 1911 H.K. Onnes discovers superconductivity and hints on superfluidity (4K)
- 1924ff Bose and Einstein develop their ideas
- 1937 P. Kapitsa, J.F. Allen, D. Misener discover superfluidity in $^4$He (2K)
- 1972 Superfluidity of $^3$He (mK)
- 1994 Steve Chu:
  "I am betting on nature to hide Bose condensation from us.
  The last 15 years she's been doing a great job." [WKNPL]
- 1995 E. Cornell, C. Wieman, W. Ketterle discover BEC of gases
- 2001 Nobel Prize for Cornell, Wieman and Ketterle
- 2001 first BEC on a chip
- 2003 coherence in a BEC
Introduction: What is a BEC?

- simple picture
  \[ \lambda_{dB} \approx d \Rightarrow \lambda_{dB}^3 n \approx 1 \]
  \[ \lambda_{dB} = \sqrt{\frac{2\pi\hbar^2}{mk_B T}} \]
  \[ T_C = \frac{2\pi\hbar^2}{mk_B} n^{2/3} \approx 5.07 \cdot 10^{-45} \frac{n^{2/3}}{m} \]

- quantum statistics
  \[ \lambda_{dB}^3 n = 2.61... \]
  \[ T_C = \left( \frac{n}{\zeta \left( \frac{3}{2} \right)} \right)^{\frac{2}{3}} \frac{2\pi\hbar^2}{mk_B} \approx 2.61 \cdot 10^{-45} \frac{n^{2/3}}{m} \]

- influence:
  - atom-atom IA
  - potential well

http://cua.mit.edu/ketterle_group/
Lasercooling

- laser slows down atoms => cooling

- limit
  - no net momentum by emmission but standard deviation \( \neq 0 \)
  - shot noise of laser \( \Delta N = \sqrt{N} \)
  - for small intensities
    - detuning \( \delta = \frac{\gamma}{2} \)
    - Doppler temperature
      \[
      T_D = \frac{\hbar \gamma}{2k_B} \approx 130 \mu K
      \]

- More sophisticated: polarisation gradient cooling, \( T = \) several 100nK
Magneto-Optical Trap

- idea
- realisation

[Laser & Photon Rev. 1, 12-23 (2007)]
Forced evaporative Cooling

- reduce potential wall by tuning “outside” field/saddle point

- thermal scalpel

[www.physnet.uni-hamburg.de/ilp/de/qoptik_07_08/Kapitel3C_07_08.pdf]
Confining and Cooling Atoms

- general remarks
  - challenge/trade-off

<table>
<thead>
<tr>
<th>density</th>
<th>high</th>
<th>low</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- better evaporation</td>
<td>- less absorption/optical methods</td>
</tr>
<tr>
<td></td>
<td>- rethermalisation</td>
<td>- no conventional condensing</td>
</tr>
</tbody>
</table>

- duty cycle [Sci 269, 198], one out of numerous
  1. collect atoms (RT, 10^{-11}torr) from gas in MOT, 300s
  2. adjust gradient and laser to cool and compress, 20\mu K
  3. magnetic field and laser pumping to defined state (F=2, m_F=2)
  4. switch off lasers, turn on quadrupole field and rf-field, 1ms
  5. ramp quadrupole field to maximum adiabatically
  6. forced evaporative cooling, 70s
  7. equilibration 2s
  8. measure absorption image

BEC? yes

- no conventional condensing
Confining and Cooling Atoms

TABLE I. Typical phase-space densities ($\rho$) during BEC production. Numbers given are for the $^{87}$Rb apparatus.

<table>
<thead>
<tr>
<th>Stage</th>
<th>$n/(cm^3)$</th>
<th>Temperature</th>
<th>Velocity</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven</td>
<td>$10^{13}$</td>
<td>383 K</td>
<td>334 m/s</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>Thermal beam</td>
<td>$10^7$</td>
<td>n/a</td>
<td>334 m/s</td>
<td>$10^{-20}$</td>
</tr>
<tr>
<td>Slowed beam</td>
<td>$10^7$</td>
<td>n/a</td>
<td>43 m/s</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>Loading MOT$^b$</td>
<td>$10^{10}$</td>
<td>150 $\mu$K</td>
<td>210 mm/s</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Compressed MOT$^b$</td>
<td>$10^{11}$</td>
<td>300 $\mu$K</td>
<td>300 mm/s</td>
<td>$4 \times 10^{-7}$</td>
</tr>
<tr>
<td>Molasses$^b$</td>
<td>$10^{11}$</td>
<td>10 $\mu$K</td>
<td>54 mm/s</td>
<td>$6 \times 10^{-5}$</td>
</tr>
<tr>
<td>Magnetic trap</td>
<td>$10^{11}$</td>
<td>500 $\mu$K</td>
<td>380 mm/s</td>
<td>$2 \times 10^{-7}$</td>
</tr>
<tr>
<td>BEC transition</td>
<td>$3 \times 10^{13}$</td>
<td>500 nK</td>
<td>12 mm/s</td>
<td>2.61</td>
</tr>
<tr>
<td>Pure BEC</td>
<td>$10^{14}$</td>
<td>(250 nK)$^c$</td>
<td>8.5 mm/s</td>
<td>(100)</td>
</tr>
</tbody>
</table>

$^a$Most probable.
$^b$Typical values, not measured separately.
$^c$Chemical potential.

Choice of examined atoms

$^{87}$Rb $^{23}$Na
$^7$Li $^1$H
$^{85}$Rb $^4$He
$^{41}$K $^{133}$Cs
$^{174}$Yb $^{52}$Cr
$^6$Li

[http://cua.mit.edu/ketterle_group/Nice_pics.htm](http://cua.mit.edu/ketterle_group/Nice_pics.htm)

[http://cua.mit.edu/ketterle_group/Nice_pics.htm](http://cua.mit.edu/ketterle_group/Nice_pics.htm)
BEC in Dilute Cold Gas Clouds

Science 269, 198 (1995) Boulder, $^{87}$Rb, $T_c \approx 170\text{nK}$, $n=2.5 \cdot 10^{12}\text{cm}^{-3}$, $N=2000$

PRL 75, 1687 (1995) Rice, $^7$Li, $N=2 \cdot 10^5$

PRL 75, 3969 (1995) MIT, Na, $T_c \approx 2\mu\text{K}$, $N=5 \cdot 10^5$, $n=10^{14}\text{cm}^{-3}$

Nobel Prize 2001
Micropotentials

- Basics
  - trapping by dipole IA
    \[ E = -\mu B \]
  - "low-field-seekers":
    \[ E = \mu B(r) \]
  - adiabaticity:
    \[ \partial_t \omega \ll \omega_L^2 \quad \omega_L = g_F \mu_B \frac{B}{\hbar} \]
  - trap position
    \[ (x = 0, \quad y = \frac{I\mu_0}{2\pi B_{bias}}) \]
  - harmonise potential
    \[ B(r) = \sqrt{b^2 r^2 + B_{off}} = B_{off} + \frac{1}{2} \frac{b^2}{B_{off}} r^2 + \cdots \]

[Rev.Mod.Phys. 79, 235 (2007)]
[Sci 307, 860 (2005)]
[Laser&Photon.Rev. 1, 112-23(2007)]
Micropotentials

- Z- and U-shape
- double-wire potential
- Y-junctions, splitters and beam guides

real chips

[Laser&Photon.Rev. 1, 1,12-23(2007)]
[Rev.Mod.Phys. 79, 235 (2007)]
[Sci 307, 860 (2005)]
BEC on a chip

TOF:

\[ T_{\text{exp}} = 630 \text{nK} \]
\[ T_{\text{theo}} = 670 \text{nK} \]

11000 atoms

Magnetic conveyor belt

Electroplated Cu-wire

\( w/\mu m \ 30, 11, 3, 3, 3, 11, 30 \)
\( h/\mu m \ 2.5 \)

\[ T_C = 730 \text{nK}, \ N_0 = 7.5 \times 10^5 \]
Coherence in Microtraps

- first a small excursion: Rabi- vs Ramsey spectroscopy

\[ \Delta \nu = 1.072 \frac{v_{th}}{\ell} \]

[Gerthsen Physik, 23Ed]
Coherence in Microchip Traps

Rabi oscillation

\[
\frac{\Omega_{2\phi}}{2\pi} = 0.32\text{kHz}
\]
\[
\frac{\Omega_{mw}}{2\pi} = 1.8\text{MHz (calculated)}
\]

Ramsey oscillation

- (pulse) sequence
  \[T_H - \pi/2 - T_R - \pi/2\]

\[\delta_R = 6.4\text{Hz} \quad \tau_C = (2.8 \pm 1.6)\text{s}\]
Atom-Surface Interactions

- calibrate \( d \)
  - projection method for \( d > 10 \mu m \)
  - for \( d < 10 \mu m \)
    - simulation taking attractive surface potential into account

- magnetic field fluctuations spin-flip near surface life time limit
- \( \tau_{N|0>} = 10s \) \( d > 20 \mu m \), \( \tau_{N|0>} = 1.6s \) \( d = 4 \mu m \)
- adjust \( T_R + T_H \) so that time near surface is constant loss of coherence vs. loss of atoms
Atom Clock on a Chip

- Allan standard deviation
  \[ \sigma_y^2(\tau) = \frac{1}{2} \langle (y_{n+1} - y_n)^2 \rangle \]
  \[ y_n = \left\langle \frac{\Delta \nu}{\nu} \right\rangle_n \]

- reasons
  - field fluctuations
  - detection system
  - density-dependent collisional shift

\[ \sigma(\tau) = 1.7 \times 10^{-11} \tau^{-1/2}/\sqrt{\text{Hz}} \]
BEC and gravity

- Why weightlessness?
  - world record: $500pK \leq E_{pot}$ of Rb at 5nm, BEC expand more, without levitating fields -> lower trapping potential -> lower groundstate energy -> lower temp.
  - larger BEC clouds are easier to focus optically, spatial resolution
  - study ultra-weak long range IA
  - free unperturbed evolution can be extended, coherence
  - study mixtures of different gases
Microgravity

- Micro-traps and macro-drops – the ZARM drop tower

QUANTengase Unter Schwerelosigkeit (2004)
QUANTum gases In Weightlessness

[www.zarm.uni-bremen.de]
[www.physik.hu-berlin.de/qom/research/droptower]
Microgravity

- technological conditions
  - miniaturisation fit to capsule 60x60x215cm
  - low weight, capsule limit 230kg, also cost-effective space launch
  - low power, batteries have limited energy
  - mechanical stability, 50g in drop tower, vibrations and shocks in space mission
  - low cycle time, drop only 4.74s
  - automation and remote control, include computer
BEC coupled to nanoresonator

- Zeeman IA
- adjustable knob: detuning
- measured quantity: rate

\[ H = -\mu \vec{B}_r(t) = \mu_B g_F F_x G_m a(t) \]
\[ \delta = \omega_r - \omega_L \]
\[ \omega_L = \mu_B g_F \frac{B_0}{\hbar} \]

Resonator
- Oscillation
  \[ a(t) = a_0 \cos(\omega_r t + \phi) \]
- Magnetic field
  \[ \vec{B}_r(t) = G_m a(t) \vec{e}_x \]

\[ \Gamma_r \]

[PRL 99,140403 (2007)]
Matter-wave interferometry

[PRA 72, 21604 (2005)]

[Nat. Phys. 1, 57-62 (2005)]
Final Words

- It’s a large field of research and rapidly growing !!
- Advantages towards conventional BEC:
  - lower vacuum restrictions
  - smaller
  - better stability, flexibility of potentials
  - faster
- Model system for 1D, 2D, 3D quantum gases
- Disordered systems
- Cosmology
- Questions of superfluidity / superconductivity
- Entanglement (s. last week)
- Quantum information processing
  - Optical lattices
  - Integrated optics refraction, diffraction on a chip
  - Microtraps
- Integrated atom optics
- Atom-laser, matter-wave interferometry
- Precision sensing: gravity, acceleration, rotation, magnetic forces
- Atom surface interactions
- Atom-nanostructure interface
- Majorana spin flips
- Sense particular current path in heterostructure
- New phenomena !
- Cool the chips, superconductors instead of Ag, Cu, …
- Electrodynamica traps for spinless neutral atoms [PRL 96, 123001 (2006)]
Thank you
for your attention !!
Vielen Dank für Ihre
Aufmerksamkeit !