Laser Cooling, Atom Traps

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Overview

• Motivation
• Cooling
• Atom Traps
Nobel Price

„for development of methods to cool and trap atoms with laser light“

Physics Nobel Price 1997

- Steven Chu 
  Stanford University

- Claude Cohen-Tannoudji 
  Collège de France und 
  Ecole Normale Supérieure

- William D. Phillips 
  National Institute of Standards and Technology
Advantages of cold atoms

room temperature: velocities on the order of 300 m/s

=> only short observation time
=> too fast for trapping
=> disturbing effects:
  · Doppler shift
  · relativistic time dilation

=> displacement and broadening of the spectral lines

=> for exact observation slow/cold atoms are needed
Motivation
Cooling
Atom Traps

Doppler Cooling
PG Cooling
VSCPT

Basics: Two level atom

\[ \hbar \delta = \hbar \omega_L - \hbar \omega_A \]

\( \delta < 0 \Rightarrow \text{detuned to the red} \)

\( \delta > 0 \Rightarrow \text{detuned to the blue} \)
Basics: Photon Absorption / Emission

**Absorption**: one direction

$$\Delta p = -n \cdot \hbar k = -n \cdot \hbar \cdot \frac{\omega_L}{c}$$

$$\Delta v = -n \cdot \frac{\hbar k}{m} = -n \cdot \hbar \cdot \frac{\omega_L}{m \cdot c}$$

**Emission**: spontaneous, isotropic

$$\langle \Delta p \rangle = 0$$

$$\langle \Delta v \rangle = 0 \Rightarrow \text{Cooling}$$
Doppler Effect

Atom moves towards the laser beam => Doppler effect

=> Shifted resonance frequency: \( \omega'_A = \omega_A - kv \)

Ideal laser detuning: \( \omega_L = \omega'_A \)

Problem: \( \omega'_A \) changes, atom goes out of resonance

Example: Sodium (Na):
natural linewidth: \( \Gamma/2\pi = 10\text{Mhz}, \lambda_{\text{res}} \sim 600\text{nm} \)
=> out of resonance after absorbing 200 photons
 corresponds to a change in velocity of \( \sim 6\text{ m/s} \)

Solution: „frequency chirp“, Zeeman Slower
**Zeeman Slower**

**Idea:**

Zeeman energy of states with $m > 0$ decreases with the decreasing field $\Delta E \sim \Delta B$

for reaching this energy states $\sigma+$ light is used

$\Rightarrow$ the increasing of $\omega_A$ is compensated by the decreasing of the Zeeman energy.

$\Rightarrow$ the atoms don't get out of resonance

Zeeman slower and frequency chirp methods are used for precooling atoms
Doppler Cooling / Optical Molasses

Two counterpropagating laser beams

no atomic beam => no special direction of movement

aim: atoms absorb mainly photons moving towards them
Doppler Cooling / Optical Molasses

Two counterpropagating laser beams

\[ \omega_L < \omega_A \quad \omega_A, v \quad \omega_L < \omega_A \]

doppler effect

=> the resonance frequency for the laser in front of the atom is shifted downwards

=> if the lasers are detuned to the red the laser in front of the atom is closer to resonance

=> mainly counterpropagating photons are absorbed
Doppler Cooling / Optical Molasses

ideal detuning: $\delta \approx -\Gamma/2$

=> net force is nearly linear in velocity and always opposes the velocity $F = -\alpha v$

=> atoms are viscously confined

3 dimensional cooling:

6 beams arranged as 3 orthogonal pairs
**Problem:**
every spontaneous emission causes random velocity change $\Delta v$

$\Rightarrow$ random walk in velocity space
$\Rightarrow$ heating
$\Rightarrow$ temperature limit

*lowest possible temperature:*
cooling is balanced by heating

$$k_B T_D = \frac{\hbar \Gamma}{2}$$

Sodium: $T_D \approx 240\, \mu K$
AC – Stark - Effect

Changing electromagnetic field creates an induced dipole moment which interacts with the field

=> atomic energy levels are shifted

$$\Delta E \sim \frac{\Omega^2}{\delta}$$

Rabi – Frequency:

$$\Omega \sim \chi_{ge}$$

=> $$\Delta E \sim \text{intensity of a transition}$$
$$\Delta E < 0$$ if the laser is detuned to the red
Polarization – Gradient Cooling

Two counterpropagating laser beams with orthogonal polarization

=> total field has circular polarization every \( \lambda/4 \)

Example

ground state \( g \) with \( J_g = 1/2 \)

exited state \( e \) with \( J_e = 3/2 \)
**Polarization – Gradient Cooling**

- $\sigma^-$: atoms are optically pumped into the $g_{-1/2}$ state

- $\sigma^+$: atoms are optically pumped into the $g_{+1/2}$ state

$\Delta E \sim$ intensity of a transition

$\Delta E < 0$

$\Rightarrow \sigma^-:$
- potential valleys for $g_{-1/2}$
- potential hills for $g_{+1/2}$

$\sigma^+:$
- potential valleys for $g_{+1/2}$
- potential hills for $g_{-1/2}$
**Polarization – Gradient Cooling**

**Sysiphus-Effect:**

- pumping takes finite time $T_P$
- atom starts in $g_{-1/2}$
- looses kinetic energy by climbing the potential hill
- after $T_P$ (ideal: on top) atom is pumped into lower state $g_{+1/2}$
- energy loss trough emission of blue shifted photon
Polarization – Gradient Cooling

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- pumping takes finite time $T_P$
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**Limit : Recoil Limit**

recoil of a single photon

$$E = \hbar^2 k^2 / 2m$$

$\Rightarrow$ Sodium: $T_R \approx 0.77 \mu K$

![Energy Level Diagram]
Velocity Selective Coherence Population Trapping

Idea:

Between two counterpropagating laser beams atoms make a random walk in velocity space

=> sometimes an atom has $v = 0$

those atoms are optically pumped into a nonabsorbing „dark state“

=> the longer you wait the more atoms have $v = 0$
2 Laser beams with the same intensity

3 state atom:
2 ground states |g-> and |g+>
1 excited state |e0>

the intensities of the two transitions |g±> -> |e0> have to interfere destructively
\( v = 0 \)

=> due to stimulated emission the \(|e_0\rangle\) state can change into a superposition of \(|g+\rangle\) and \(|g-\rangle\)

\[
\Psi_{SP} = \frac{1}{\sqrt{2}} \left( |g+\rangle + |g-\rangle \right)
\]

because of the destructively interfering transition intensities this is a dark state for the light

\( v \neq 0 \)

=> due to doppler shifting the two beams have not the same intensity from the view of the atom

=> the dark state can not be reached
**Velocity Selective Coherence Population Trapping**

\[ \mathbf{v} = 0 \]

=> due to stimulated emission
the \(|e_0\rangle\) state can change into a superposition of \(|g+\rangle\) and \(|g-\rangle\):

\[ \Psi_{SP} = \frac{1}{\sqrt{2}} (|g_+\rangle + |g_-\rangle) \]

because of the destructively interfering transition intensities this is a dark state for the light

\[ \mathbf{v} \neq 0 \]

=> due to doppler shifting the two beams have not the same intensity from the view of the atom
=> the dark state can not be reached
**Problem:**

atoms are neutral

=> electric fields can not be used for catching atoms

=> for cooling them laser cooling is necessary

the first trapping experiments were done with ions.

-> in contrast ions can easily be slowed down and caught with electric fields

trapping atoms was not achieved until after the invention of laser cooling (first proposed in 1975 by Hänsch and Schawlow and Wineland and Dehmelt)
**Quadrupole Trap**

**Idea:**
Zeeman energy of quantum states with $m > 0$ increases with increasing magnetic field *(low field seekers)*

$\Rightarrow$ atoms can be caught in field minima

$\Delta E = g \mu_B m \Delta B$

*typical dept $< 0.1T$ corresponds to $0.05K$ and $7m/s$ (Na)*

**Problem:**
- the trap only works with the right quantum states
- no further cooling
Idea:

The Quadrupole field shifts the Zeeman energy levels

=> imbalance between the radiation forces

=> atoms are pushed back to the center
Example:

atom moves in +z direction

=> the lasers come into resonance with the M = -1 state

because of the selection rules only the $\sigma^-$ light interacts with the atom

=> the atom is pushed back to the centre

=> trapping combined with cooling
Motivation
Cooling
Atom Traps

Quadrupole Trap
MOT
Dipole Force Trap

Dipole Force

Based on the **AC Stark effect**

=> energy levels are shifted in a laser beam

=> dipole force

\[ F_{\text{dipole}} = \alpha I \]

\( \alpha \) = atomic polarizability

\( I \) = laser intensity

=> for *detuning to the red* atoms are attracted into the regions with high intensity
Dipole Force Trap

A focused laser beam confines atoms in all directions

=> dipole force trap

Optical tweezers:

Atoms or even molecules can be trapped in the focus of a laser beam. If the focus is moved the trapped particles follow.
A BEC is a State of matter formed by bosons near the absolute 0

Due to cooling T falls below a critical temperature Tc

\[ \lambda(T_c) \approx d(T_c), \quad T_c \propto \frac{1}{m} \cdot n^{3/2} \]

=> a large number of atoms collapses into the lowest quantum state

in this state the atoms are fully delocated in the area of the condensate

=> the state of the whole condensate can be described as a single matter wave
Bose Einstein Condensation

1.) temperature sharply over $T_c$
   almost classical distribution of atoms

2.) phase transition $\Rightarrow$ sharp peak of
    atoms in the trap centre

3.) further cooling increases the condensate
    fraction to almost 100%
Bose Einstein Condensation

1.) temperature sharply over $T_c$
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BEC Application: Atom Laser

**Idea:**

Bose Einstein Condensate is held in a magnetic trap

=> only states with \( M > 0 \) are trapped

=> if \( M \) is changed to a value \( \leq 0 \) atoms are no longer trapped (done with radio frequency pulses)

=> atoms leave the trap due to gravitational force

=> source of moving clouds of atoms in the same quantum state = *atom laser*
Both laser cooling and atom traps made it possible to observe atoms more exactly. Makes high precision spectroscopy of atoms possible.

Effects like Bose Einstein Condensation / fermi Condensation could only be shown with these mechanisms.

In future lots of applications of ultracold atoms are thinkable for example

- **atom interferometry**
  -> an atom interferometer would be more precisely than one with light because of the smaller wavelenght

- **atom holography**
  -> projection of electronic circuits onto semiconductors
  -> would also profit of the smaller wavelenght compared to light