Atom meets Photon

Atom traps
(Atomfallen)

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http://etc.usf.edu/clipart/4400/4465/hand_9.htm
1. atom trap

2. four different atom traps

3. summary
\[ E_{\text{kin}} = \frac{3}{2} k_B T \]

\[ E_{\text{pot}} = ? \]
\[ \vec{F} = -\nabla U \]

**Forces:**
- radiation pressure
- optical dipole
- magnetic
- electric

(only consider neutral atoms)

**Summary:**
- trap frequency
- size of the trap
- depth of the trap
- heating rate
- time constant of the trap
Magneto-optical trap
(Raab, Chu "Trapping of neutral sodium atoms with radiation pressure" 1987)

- ~$10^{10}$ atoms
- diameter of a few mm
1dim case:

- Energy diagram with states $\sigma^+$ and $\sigma^-$ interacting with laser frequency $\hbar \omega_{\text{Laser}}$.
- Inhomogeneous magnetic field: $B(z) = bz$.
- Energy shift: $\Delta E = \mu m_s B = \mu b m_s z$.

3dim case:

- Laser beams coupling states $\sigma^+$ and $\sigma^-$.
- Magnetic field $B$ in $z$ direction.
- Transition probabilities and selection rules.

Summary:

- MOT (Magneto-Optical Trap) principles and applications.
atom trap | MOT | dipole | magnetic | electric | summary

advantages: • cooling and trapping
• cooling down to ~10μK
• capture velocity of a few K

disadvantages: • near resonant light → perturbed internal dynamics
• achievable density limited by photon reemission and reabsorption
• certain requirements to atom structure

heating: • temperature limited by doppler effects
• background pressure
Dipole trap

- ~500 Na atoms
- ~10µm diameter

Chu Experimental observation of optically trapped atoms 1986
\[
U_{\text{dip}} = -\frac{1}{2} \langle \vec{p} \vec{E} \rangle
\]

\( \omega \) = transition frequency

\( \omega < \omega_0 = \text{red detuned} \)

\( \omega > \omega_0 = \text{blue detuned} \)
driving field $E$

\[
U_{\text{dip}} = -\frac{1}{2} \langle \vec{p}\vec{E} \rangle \\
\vec{F}_{\text{dip}}(\vec{r}) = -\nabla U_{\text{dip}}(\vec{r})
\]

\[
U_{\text{dip}}^{\text{red}} \propto -I \\
\vec{F}_{\text{dip}}^{\text{red}} \propto \nabla I
\]

\[
U_{\text{dip}}^{\text{blue}} \propto +I \\
\vec{F}_{\text{dip}}^{\text{blue}} \propto -\nabla I
\]
red-detuned trap attracts atoms towards the max. of intensity

blue-detuned trap repels atoms out of intensity maximum

dipole potential \( U_{dip}(\vec{r}) \propto \frac{I(\vec{r})}{\Delta} \)

scattering rate \( \Gamma_{sc}(\vec{r}) \propto \frac{I(\vec{r})}{\Delta^2} \)

large detunings \( \Delta = \omega - \omega_0 \) and high intensities for large potential depth and low scattering rate
first dipol-trap 1986 Chu (Nobel prize 1997)  
(Chu „Experimental observation of optically trapped atoms“ 1986)

- sodium atoms cooled in optical molasses below $10^{-3}$K  
- laserbeam tuned far away from resonance  
- $\sim 500$ atoms confined in a volume of $10^3 \ \mu m^3$  
- trap lifetimes of several seconds
<table>
<thead>
<tr>
<th>Trap Type</th>
<th>Diagram</th>
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<tbody>
<tr>
<td>Atom trap MOT</td>
<td><img src="Image" alt="Atom trap MOT" /></td>
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<tr>
<td>Dipole</td>
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<tr>
<td>Magnetic depth</td>
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<td>Electric focusd-beam trap</td>
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<td>Standing-wave trap</td>
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<td>Crossed-beam trap</td>
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<tr>
<td>Optical-lattice trap</td>
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<tr>
<td>advantages:</td>
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<tr>
<td>---------------------------------------------------------------------------</td>
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<td>• far-detuned light causes weak interaction and</td>
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<td>therefore optical excitation can be kept very low</td>
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<tr>
<td>• trapping times of many seconds</td>
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<tr>
<td>• great variety of different trapping geometries</td>
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<td>• easily moveable</td>
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<td>disadvantages:</td>
<td></td>
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<tr>
<td>• loading with precooled atoms</td>
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<tr>
<td>• no cooling</td>
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<td>heating:</td>
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<tr>
<td>• scattering processes</td>
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<tr>
<td>• red-detuned trap: atoms at intensity maximum</td>
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<tr>
<td>• blue-detuned trap: atoms at intensity minimum</td>
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<td>• background pressure</td>
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Magnetic trap

(Alan „First observation of magnetically trapped neutral atoms“ 1985)
1dim:

Energy

\[ \text{state at } B \neq 0 \]

\[ \text{state at } B = 0 \]

\[ |B(z)| \]

\[ z \]

magnetic potential

\[ U_{mag} = \mu \left| \overrightarrow{B} \right| \] (e.g. Na 3S\(_{1/2}\) \( m_F = 2 \))

magnetic force

\[ \overrightarrow{F}_{mag} = -\nabla U_{mag} = -\mu \nabla \left| \overrightarrow{B} \right| \]

Maxwell: \( \nabla \cdot \overrightarrow{B} = 0 \) only low-field seekers are possible
configurations of the inhomogeneous magnetic field in 3dim

(a) magn. quadrupol trap  (b) spherical hexapole trap  (c) ioffe trapp

T. Bergeman *magnetostatic trapping fields for neutral atoms* 1987
advantages:  • trap depths of ~100mK
  • excellent tools for evaporative cooling and Bose-Einstein condensation

disadvantages:  • trapping mechanism relies on the internal atomic state (only low-field seeker)
  • complicated geometries of the magnetic field

heating:  • background pressure
  • Majorana transitions
Electric trap

(Rieger, Rempe „Trapping of neutral rubidium with a macroscopic three-phase electric trap“ 2007)

quadratic Strark shift \[ W_s = -\frac{1}{2} \alpha |E|^2 \]

\( \alpha \) is the atom's static polarizability
With vanish in time average

Atom trap MOT Dipole Magnetic Electric Summary

\[
\vec{F}_{el} = -\nabla W_s = \alpha |E| \nabla |E| \equiv \alpha E_0 \nabla |E|
\]

with \( |E| = E_0 + bx^2 - \frac{1}{2} b(y^2 + z^2) \) vanish in time average

\[\nabla \approx \nabla = -\nabla = 0\]

\( \alpha \)

induced micromotion\( (0) \)

\[ m\ddot{x} = \sin(\omega t) \]

\[ x \propto -\sin(\omega t) \]

non-linear potential and micromotion cause net force towards the trap center

\( W_s \)

imcromotion

y-z-plane

x-direction

micromotion

\( t \)}
advantages:  • confining molecules and atoms
  • trap size of 0.3mm in diameter

disadvantages:  • ~20µK trap depth
  • need precooled atoms

heating:  • background pressure
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<td>• near resonant light</td>
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