Laser Cooling

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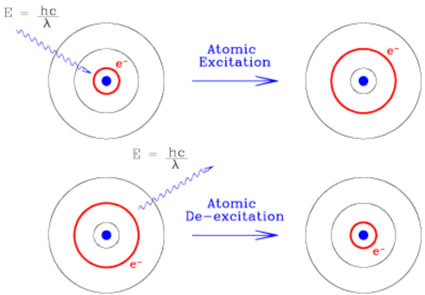
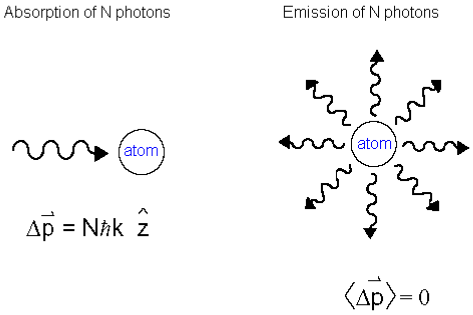
Absorption and Emission of Light



Conservation of

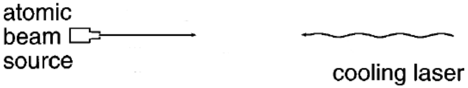
- Energy ($\hbar\omega$)
- Momentum ($\hbar k$)
- Angular momentum ($\hbar$)

Absorption and Emission of Light



- $v_r = \hbar k/M \simeq \mathrm{few\,cm/s}$
- $v_{RMS} = \sqrt{3kT/m} \approx 500\,\mathrm{m/s}$ (air at room temprature)

Beam Deceleration



- Laser beam in the opposite direction to an atomic beam
- Frequency of the laser just below the resonance frequency of the atoms
- Atoms excited to a higher state and decay back to the ground state
- maximum deceleration limited by spontaneous emission rate ($\vec{a}_{max} = \hbar\vec{k}\gamma/2M$)

Beam Deceleration

1. Maximum deceleration

$$\vec{a}_{max} = \hbar\vec{k}\gamma/2M$$

2. Scattering rate

$$\gamma_p = \frac{s_0\gamma/2}{1+s_0+[2(\delta+\omega_D)/\gamma]^2}$$

- $\delta = \omega_l - \omega_a$
- $\omega_D = -\vec{k}\cdot\vec{v}$
- maximum deceleration when $\delta + \omega_D << \gamma$

Beam Deceleration

Doppler shift depends on velocity. Ways to compensate

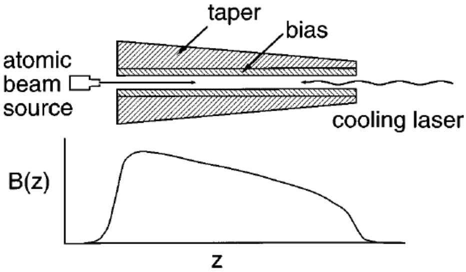
1. Laser Frequency Sweep
   - Change ω_l
2. Vary the Atomic Frequency
   - Change ω_a
     - Magnetic Field (Zeeman effect)
     - Electric Field (Stark effect)
3. Vary the Doppler Shift
   - Change ω_D
4. Broadband Light

Laser Frequency Sweep

- $\delta + \omega_D << \gamma \quad \delta = \omega_l - \omega_a$
- Change ω_l at the rate $\dot{\omega}_l \approx -\dot{\omega}_d$
- Atoms arrive in pulses

Varying the Atomic Frequency

- Spatially varying magnetic field
  - Zeeman effect shifts the resonant frequency
  - $\Delta E = g\mu_B MB$
  - Uniform deceleration $B(z) = B_0\sqrt{1 - z/z_0}$



Varying the Atomic Frequency

- Inhomogeneous DC electric field
  - Stark effect shifts the resonant frequency
  - $\Delta E = \frac{1}{2}\alpha|\varepsilon|^2$
  - Uniform deceleration $\varepsilon(z) = \varepsilon_0\sqrt{1 - \sqrt{1 - z/z_0}}$

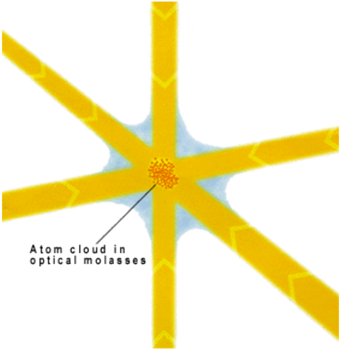
Varying the Doppler Shift

- $\delta + \omega_D << \gamma$
- $\omega_D = -\vec{k} \cdot \vec{v} = -kv\, cos\, \theta$
  - Vary θ to change the Doppler shift
- Will also change the transverse velocity component

Broadband Light

- Use white light
- Frequency range from ω_a to $\omega_a - \vec{k} \cdot \vec{v}$
- Requires a lot more light power then other methods

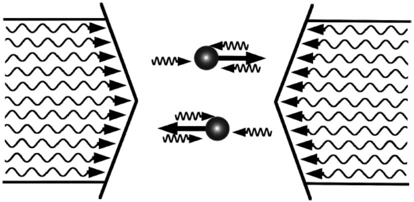
Optical Molasses

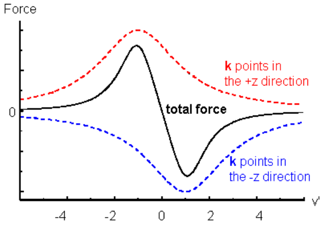


- Three pairs of counter propagating laser beams
- Lasers tuned slightly below atomic resonance

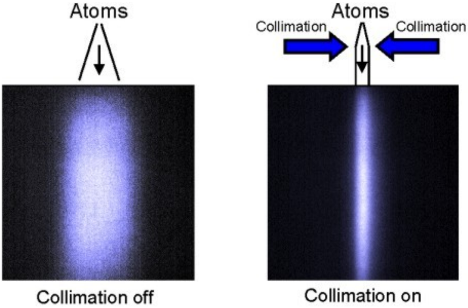
Optical Molasses

- Atoms will interact more strongly with the laser beam opposing there motion due to the Doppler shift





Atomic Beam Colimation



The Doppler Limit

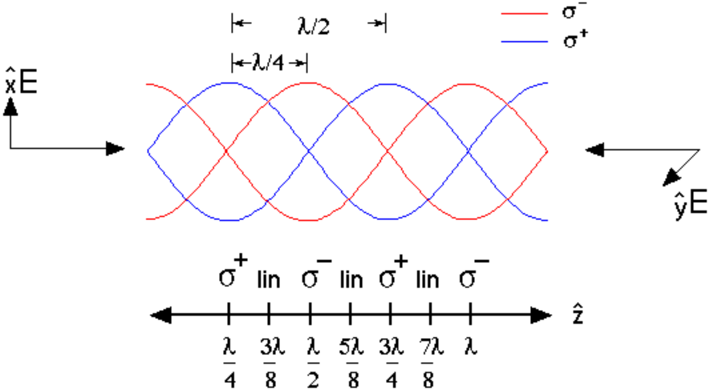
- Momentum steps in absorption and emission are discrete
- The random nature of the processes produces a random walk
- The dampening force counters this random walk (heating)
- In a steady state we obtain the Doppler temperature $T_D = \hbar\gamma/2k_b$
- T_D is usually below $1\,\mathrm{mK}$

Below the Doppler Limit

Cooling Below the Doppler Limit

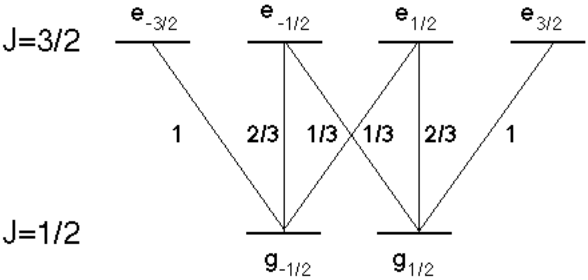
1. Linear $\perp$ Linear Polarization
2. Magnetically Induced Laser Cooling

Linear ⊥ Linear Polarization

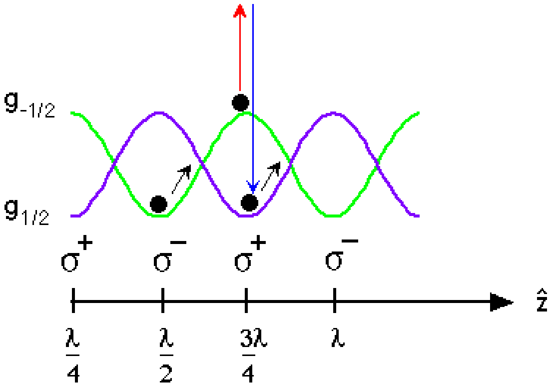


Cooling Below the Doppler Limit

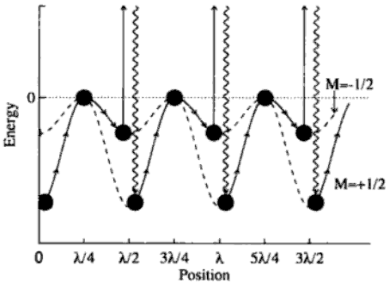
- Atom in a light field will have it's energy levels shifted due to the Stark effect
- In the low-intensity limit of two laser beams of intensity $s_0 I$
- $\Delta E_g = \frac{\hbar \delta s_0 C_{ge}^2}{1+(2\delta/\gamma)^2}$



Sisyphus Cooling



Magnetically Induced Laser Cooling (MILC)



- Standing wave of constant circularly polarized light
- Light pumps atoms to the $M_g = 1/2$ state
- Magnetic field precesses the population from $M_g = 1/2$ to $M_g = -1/2$

Application

- Bose Einstein Condensate
- Atomic Clocks