Lecture 3: laser cooling and trapping

Trapping

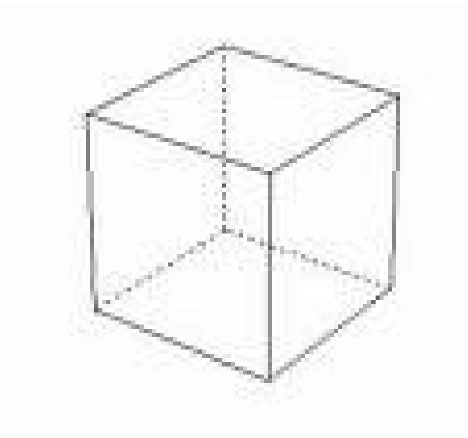
- Dipole trap
- Optical lattices

Cooling

- Radiation force
- Doppler cooling
- Optical molasses

Full Quantum treatment: Dressed atom picture

$+$

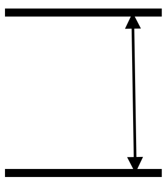


$$|\,system> = |\,atom> \otimes |\,field>$$

Atom

$|\,e>$

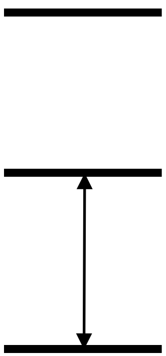
$|\,g>$



$\hbar\omega_0$

$\otimes$

field



$|\,n+1>$

$|\,n>$

$\hbar\omega$

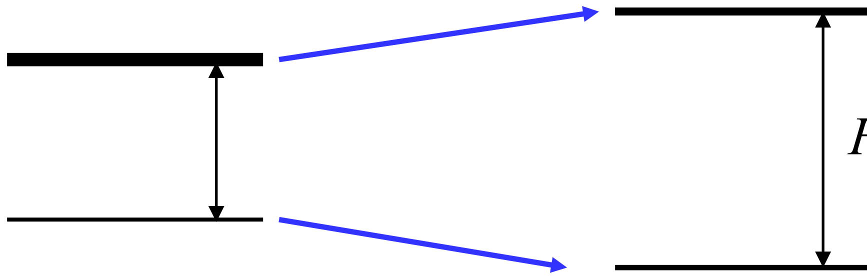
$\ldots$

Light shift with laser detuning $\delta = \omega - \omega_0$

Red detuning $\omega < \omega_0$

$|e, n>$

$|g, n+1>$



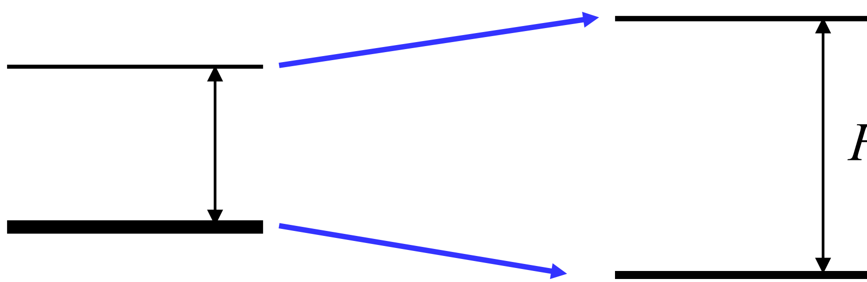
$$2\hbar\sqrt{(\delta/2)^2 + \Omega^2}$$

$$H = \hbar\begin{bmatrix} \delta/2 & \Omega \\ \Omega^* & -\delta/2 \end{bmatrix}$$

Blud detuning $\omega > \omega_0$

$|g, n+1>$

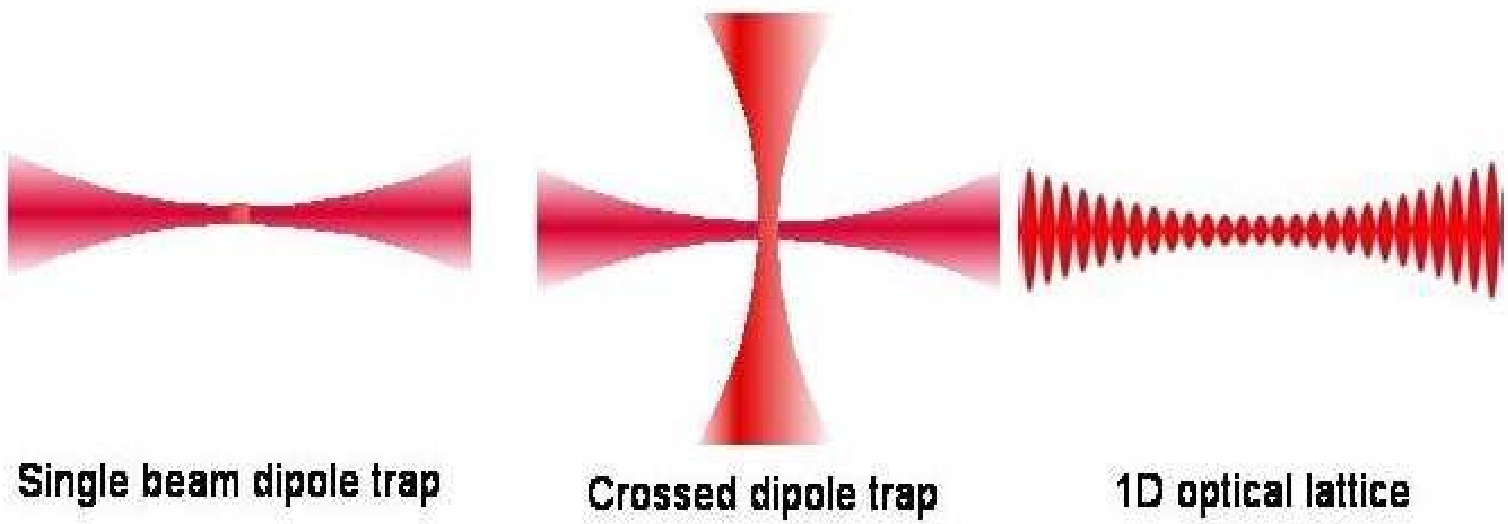
$|e, n>$



$$2\hbar\sqrt{(\delta/2)^2 + \Omega^2}$$

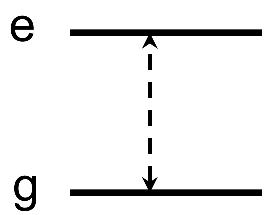
$$H = \hbar\begin{bmatrix} -\delta/2 & \Omega \\ \Omega^* & \delta/2 \end{bmatrix}$$

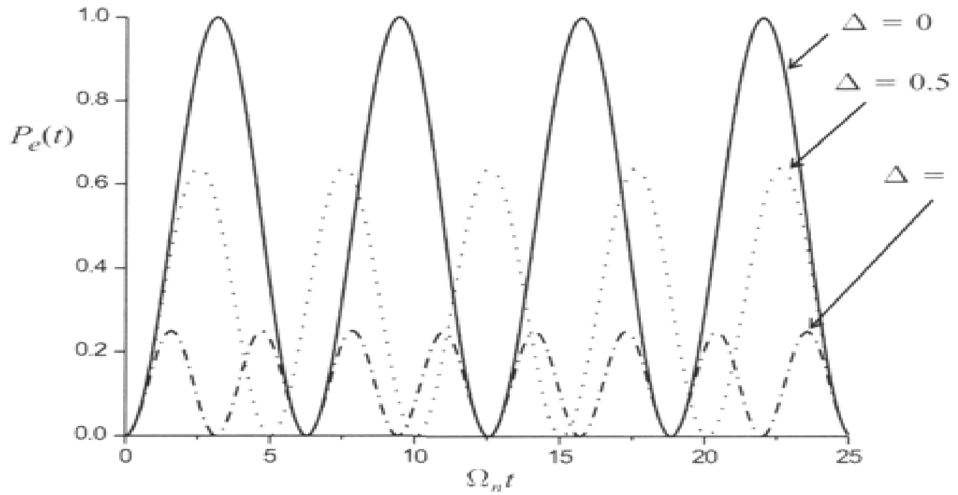
Optical Traps



Light shift $\Delta E = \frac{\hbar\Gamma}{8}\frac{\mathrm{I}/\mathrm{I}_{\mathrm{sat}}}{\Delta/\Gamma}$ Scattering rate $s = \frac{\Gamma}{2}\frac{\mathrm{I}/\mathrm{I}_{\mathrm{sat}}}{1+\Delta^2/\Gamma^2}$

Γ: atomic linewidth = 5.3 MHz for Cs atom
I_{sat}: Saturation intensity = 1.12mW/cm^2 for Cs atom
$\Delta \equiv \omega - \omega_0$: laser detuning





$$\hbar\omega_0 = E_e - E_g$$

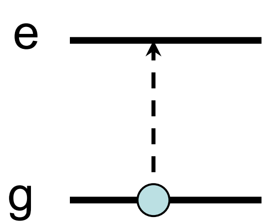
$$H = H_0 + \vec{d} \cdot \vec{E}(t)$$

$$= H_0 + \hbar\Omega\cos\omega t$$

$$= \begin{bmatrix} E2 & \hbar\Omega e^{i\omega t} \\ \hbar\Omega e^{-i\omega t} & E1 \end{bmatrix}$$

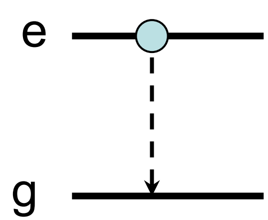
(no decay is assumed here)

Stimulated absorption



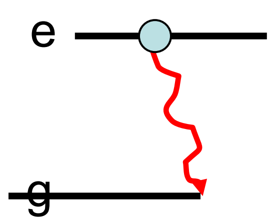
$\sigma_+ a|g,n>$

Stimulated emission



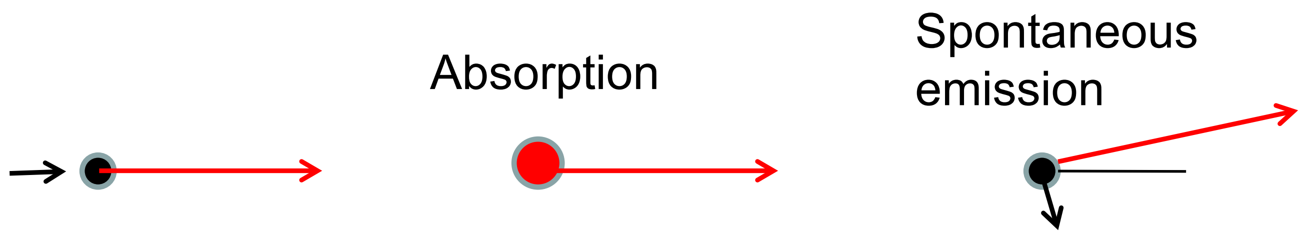
$\sigma_- a^+|e,n>$

Spontaneous emission



$\sigma_- a^+|e,0>$

Scattering = absorption followed by spontaneous emission



Energy conservation: $\frac{p_i^2}{2m} + \hbar\omega = \frac{(p_i+\hbar k)^2}{2m} + \hbar\omega_0 = \frac{(p_i+\hbar k-\hbar k')^2}{2m} + \hbar\omega'$

$$\hbar\delta = \hbar\omega - \hbar\omega_0 = \frac{\hbar}{m}\vec{k}\cdot\vec{p}_i + E_r$$

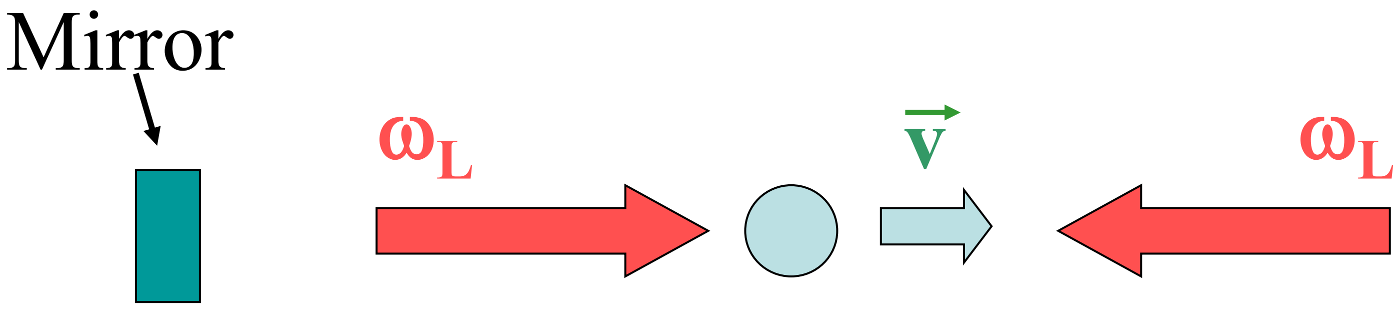
Doppler shift + recoil energy

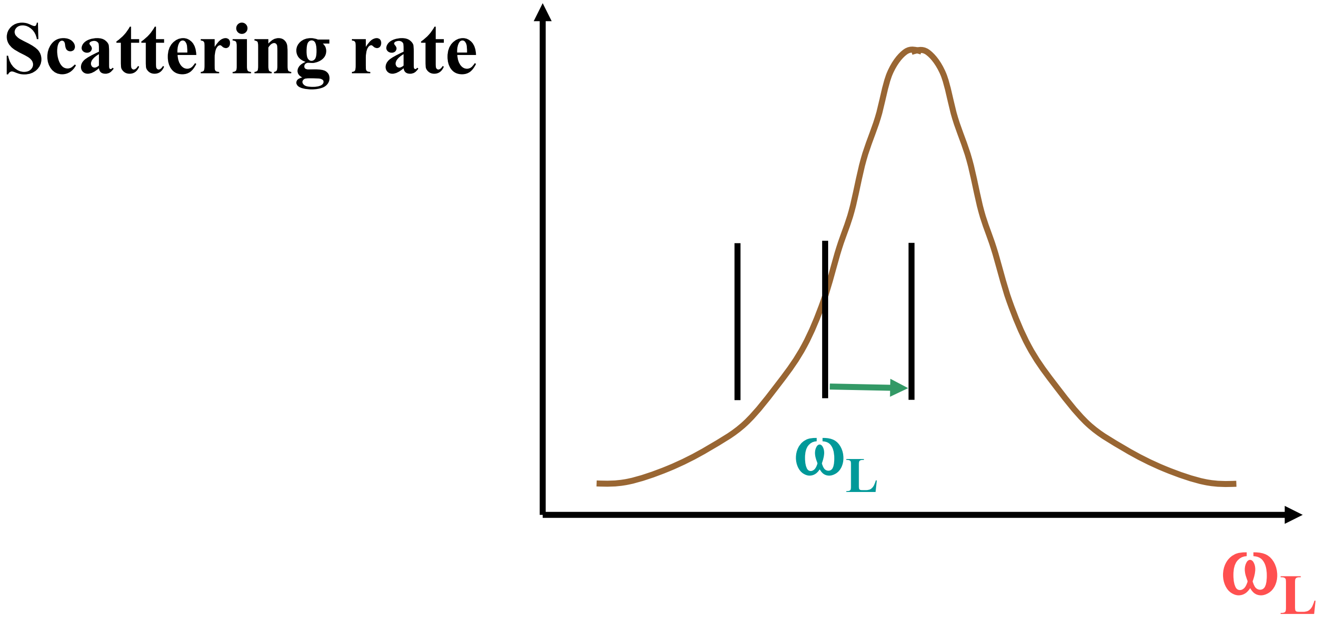
$$\hbar\delta = \hbar\omega - \hbar\omega_0 = \frac{1}{2m}(2\hbar\vec{k}\cdot\vec{p}_i + p_i^2)$$

$$\hbar\omega_0 - \hbar\omega' = \frac{1}{2m}\left(-2\hbar\vec{k}'\cdot(\vec{p}_i + \hbar k) + \hbar^2 k'^2\right) \approx E_r$$

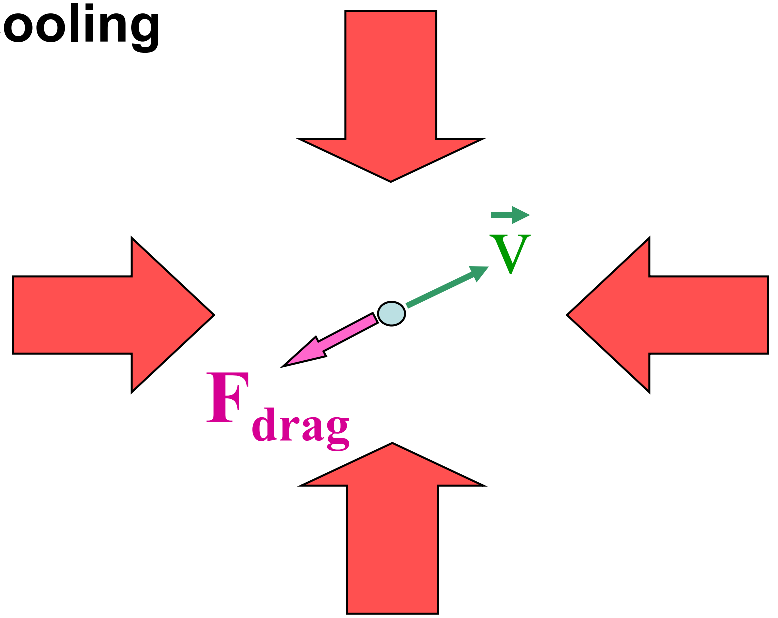
In every scattering event, kinetic energy changes by $\hbar\omega - \hbar\omega' = \frac{\hbar}{m}\vec{k}\cdot\vec{p}_i + 2E_r$

Doppler Cooling





Doppler cooling



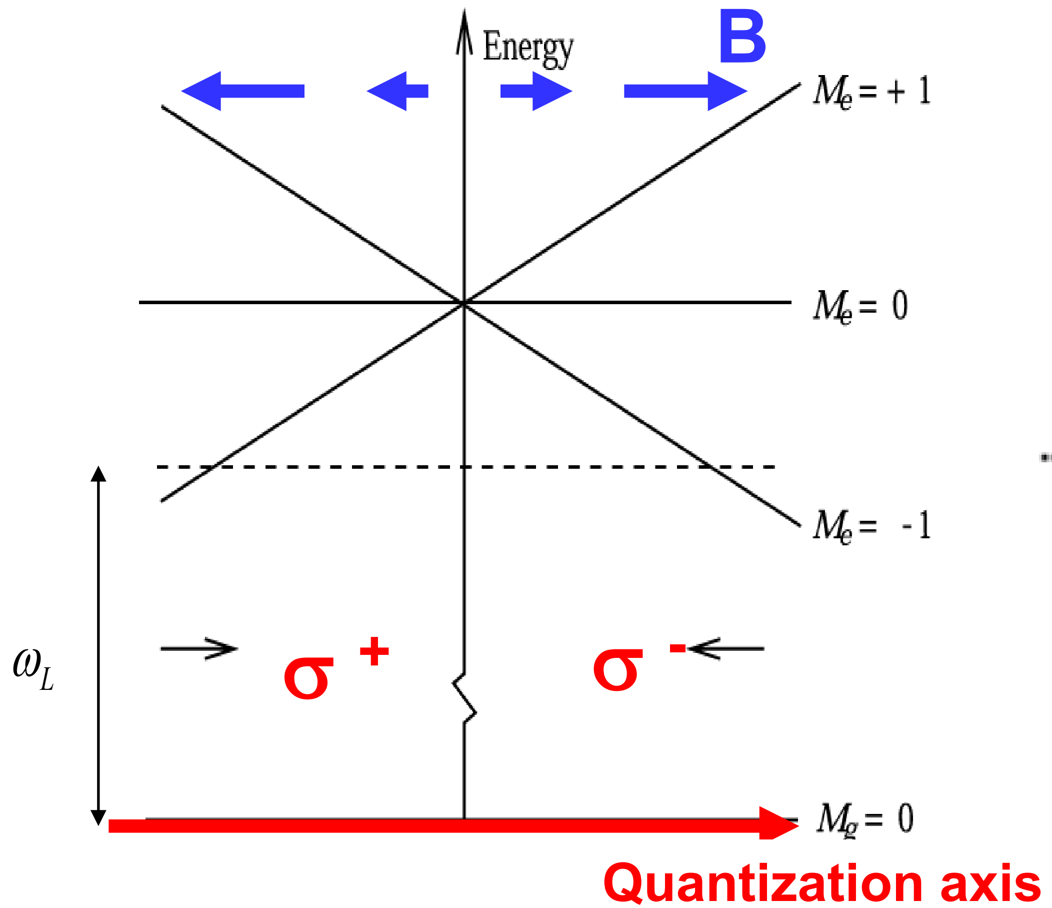
$$F_{drag} = -\alpha v \quad \text{(viscous drag force)}$$

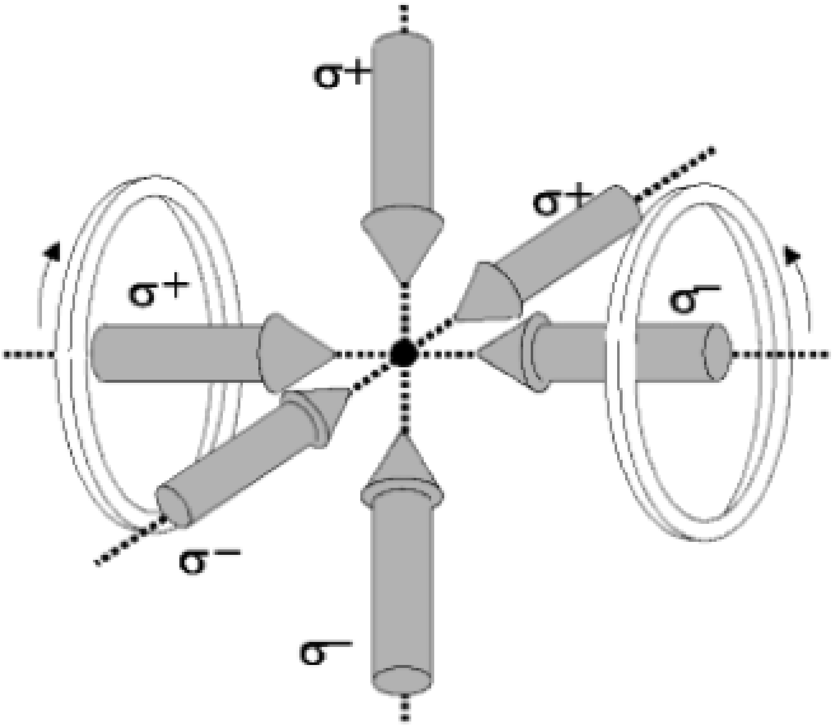
Proposal:

Hänsch and Schawlow (1975)

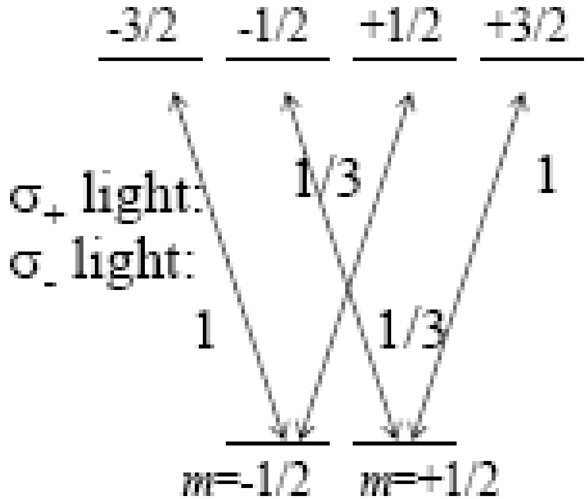
Spatial confinement: trapping
Momentum space confinement: Optical molasses

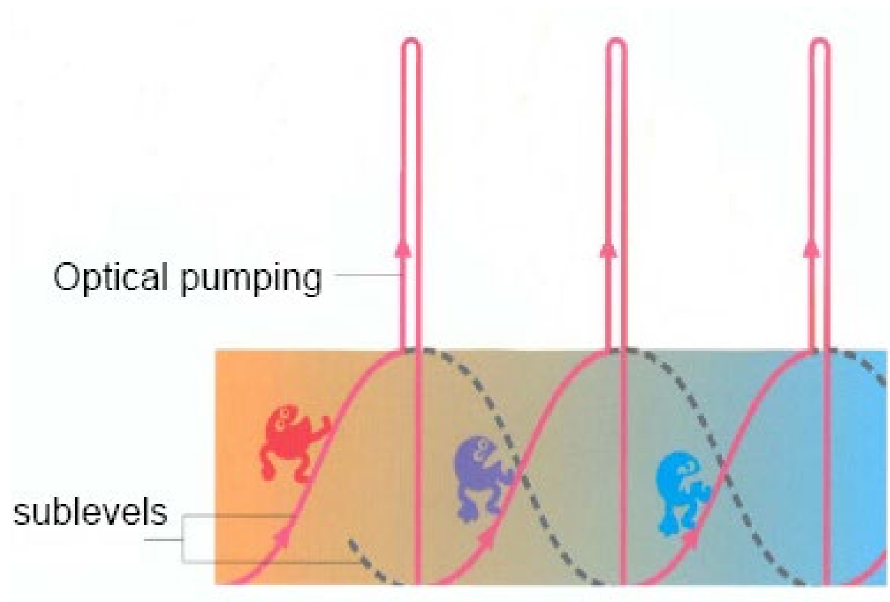
$$\mathbf{F} = -\alpha\,\mathbf{v} - k\,\mathbf{r}$$

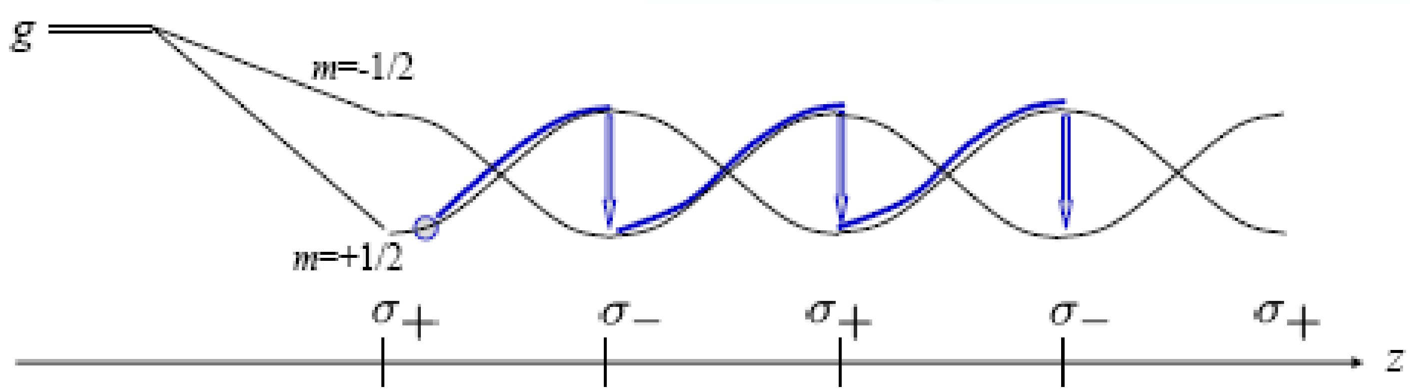




Ground state is not single level.







$k_B T \propto \frac{\text{intensity}}{\text{detuning}}$ until the recoil limit is reached $k_B T \sim \text{a few } \frac{\hbar^2 k^2}{2M}$

Polarization gradient cooling