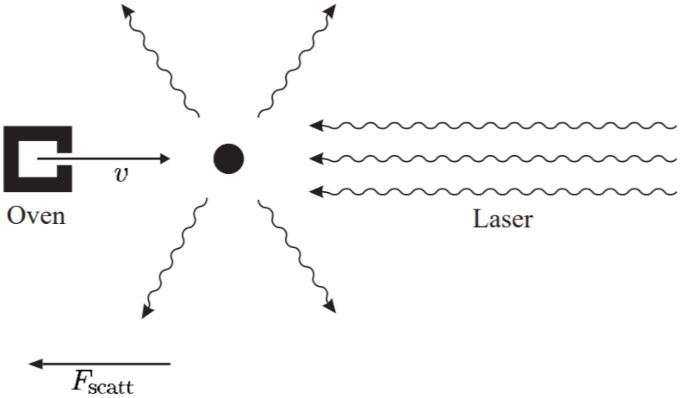
Basics of laser cooling for ions and neutral atoms

Quantum Engineering II

4th of June 2021

The scattering force

$$\delta = \omega - \omega_0 + kv,$$

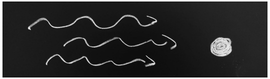


The force is given by

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = \hbar\mathbf{k} \cdot \Gamma_{\text{scat}}$$

where

$$\Gamma_{\text{scat}} = \Gamma\rho_{22} = \frac{\Gamma}{2}\frac{I/I_{sat}}{1 + I/I_{sat} + 4\Delta^2/\Gamma^2} \quad \text{(steady state)}$$



$$F_{max} = \hbar k \frac{\Gamma}{2}$$

Slowing an atomic beam

Compensation of Doppler shift by Zeeman effect shall obey:

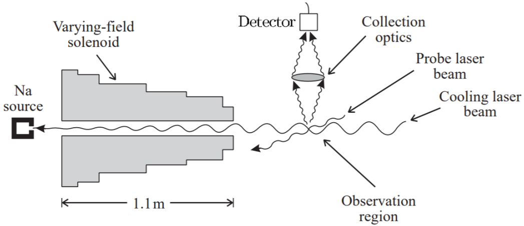
$$\omega_0 + \frac{\mu_B B(z)}{\hbar} = \omega + kv$$

The required magnetic field is then:

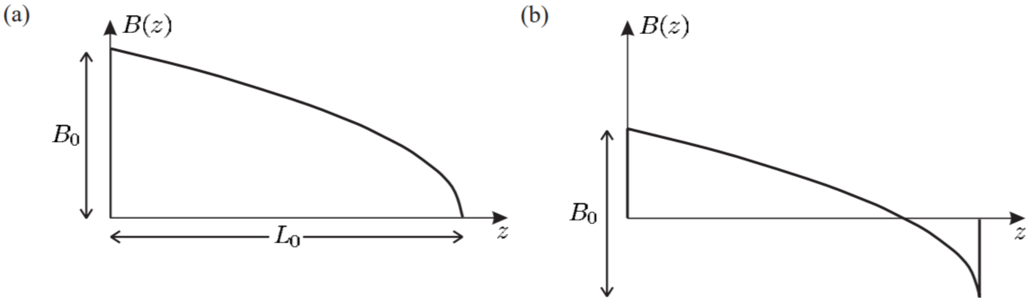
$$B(z) = B_0(1 - \frac{z}{L_0})^{1/2} + B_{bias}$$

where

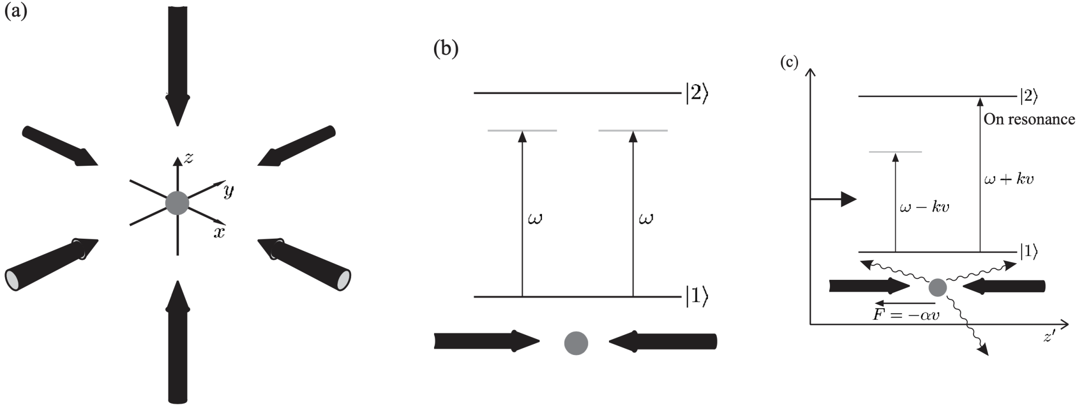
$$B_{\text{bias}} = \frac{\hbar}{\mu_0}(\omega - \omega_0)$$



Slowing an atomic beam



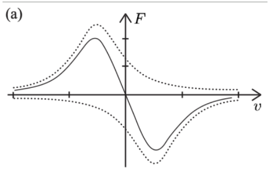
Optical molasses



Optical molasses

$$
\begin{aligned}
F_{\text{molassses}} &= F_{\text{scatt}}(\delta - kv) - F_{\text{scatt}}(\delta + kv) \\
&= -2\frac{\partial F}{\partial \omega}kv, \quad kv \ll \Gamma \\
&= -\alpha v
\end{aligned}
$$

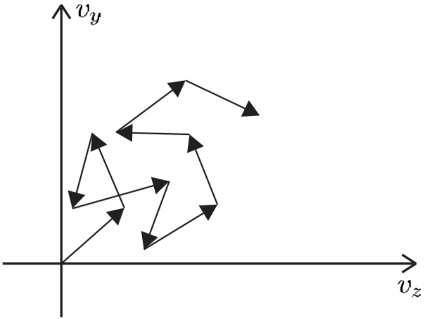
$$
\alpha = 2k\frac{\partial F}{\partial \omega} = 4\hbar k^2 \frac{I}{I_{\text{sat}}}
$$



Cooling Limit

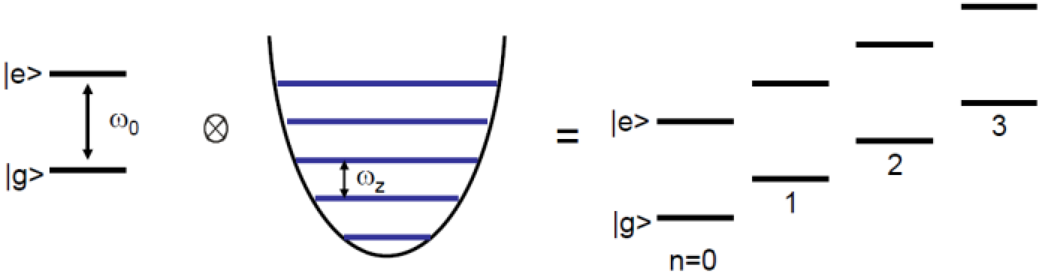
$$\mathbf{F} = \mathbf{F}_{\mathsf{abs}} + \delta\mathbf{F}_{\mathsf{abs}} + \mathbf{F}_{\mathsf{spont}} + \delta\mathbf{F}_{\mathsf{spont}}$$

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



Resolved Sideband Cooling

Laser cooling trapped ions in linear Paul trap. Motion in x, y is quantized like harmonic oscillator



Resolved Sideband Cooling

Jaynes-Cummings model

$$H_{\mathrm{JC}} \propto \hat{a}^\dagger \hat{b} + \hat{a}\hat{b}^\dagger$$

Which drives the transistions:

$$|g\rangle|n\rangle \iff |e\rangle|n-1\rangle$$

Spontaneous emission climbs down the later