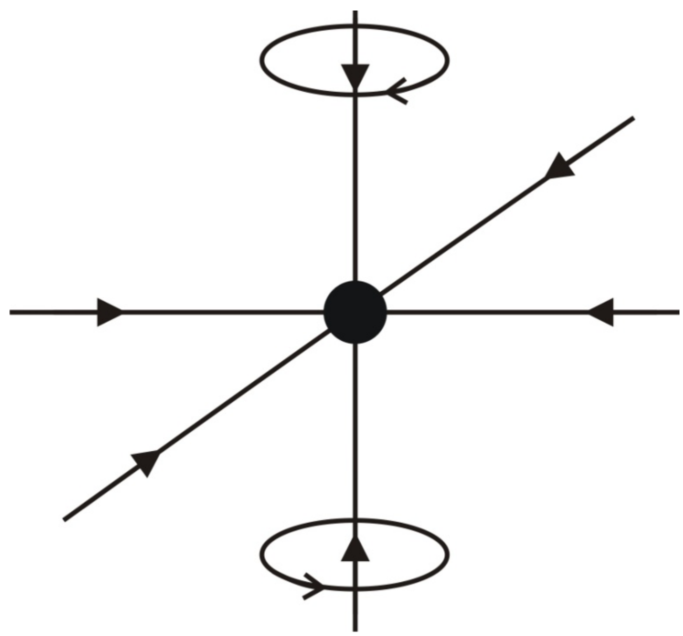
Physics 4062/5062 – Lecture One

Outline

Applications of Laser Cooled Atoms

- Inertial Sensing
- Precision Measurements
- Atomic Clocks
- BEC → Condensed Matter Physics

MOT – Magneto Optical Trap (Based on radiation pressure force and magnetic interactions)



How does a MOT work?

- Laser Cooling (Damping atomic motion)
- Magnetic Forces (Trapping atoms)

Discussion of physical picture that describes these effects

Laser Cooling – Underlying Mechanism is the Doppler Shift

Review: Doppler effect for Light in analogy with Doppler effect for sound

Assume ν_o is natural frequency (rest frame) and v_x is the speed of radiating atom (1D treatment)

Source Approaching

$$\nu' = \nu_o \left(\frac{c}{c - v_s}\right) = \nu_o \left(\frac{1}{1 - \frac{v_x}{c}}\right)$$

$$\nu' = \nu_o \left(1 + \frac{v_x}{c}\right) \qquad v_x << c$$

$$\nu' > \nu_o$$

Source Receding

$$\nu' = \nu_o \left(\frac{c}{c + v_s}\right) = \nu_o \left(\frac{1}{1 + \frac{v_x}{c}}\right)$$

$$\nu' = \nu_o \left(1 - \frac{v_x}{c}\right)$$

$$\nu' < \nu_o$$

Doppler Shift

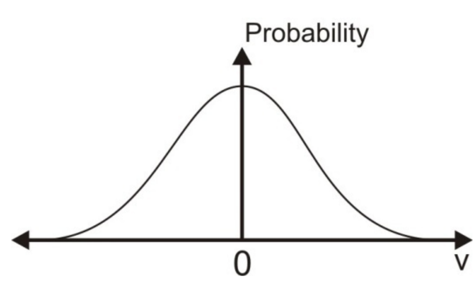
$$\nu' - \nu_o = \pm \left(\frac{v_x}{c}\right) \nu o$$

Fractional Shift

$$\frac{\nu' - \nu_o}{\nu_o} = \pm \frac{v_x}{c}$$

$$\frac{\Delta\nu}{\nu_o} = \pm \frac{v_x}{c}$$

The values of v_x correspond to 1D Maxwell-Boltzmann Distribution

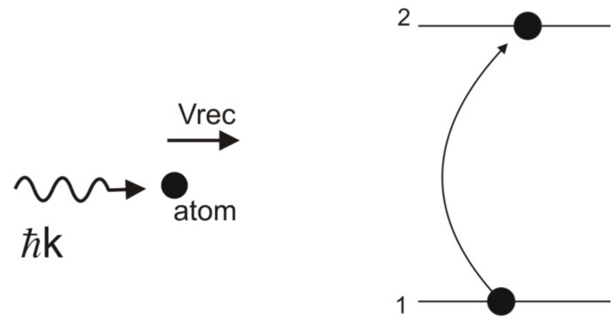


Laser Cooling – Differential Absorption due to Doppler Shift

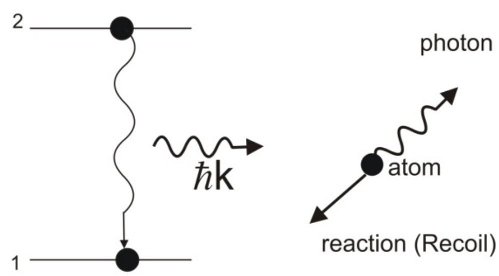
Absorption

- momentum transfer in direction of laser

$$v_{rec} = \frac{\hbar k}{m}$$



Spontaneous Emission is random and isotropic



Absorption + Spontaneous Emission gives rise to Net Force

$$a = \frac{F}{m} = \left(\frac{1}{m}\right)\left(\frac{\Delta p}{\Delta t}\right) = \left(\frac{1}{m}\right)\left(\frac{\hbar k}{2\tau}\right)$$

Can show $a_{max} = \left(\frac{\hbar k}{m}\right)\left(\frac{\Gamma}{2}\right) = v_{recoil}\left(\frac{\Gamma}{2}\right)$

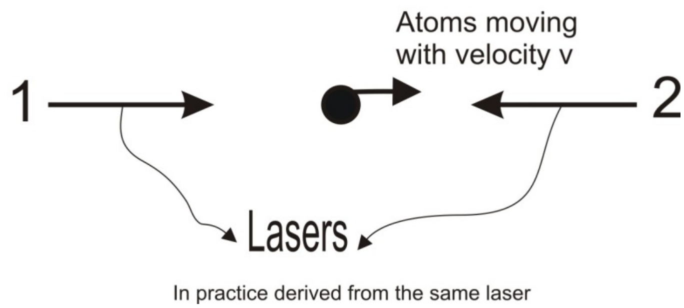
Here, τ is the lifetime of upper level and $\Gamma = 1/\tau$ is the radiative rate of the upper level

Assume that a single laser is interacting with atom

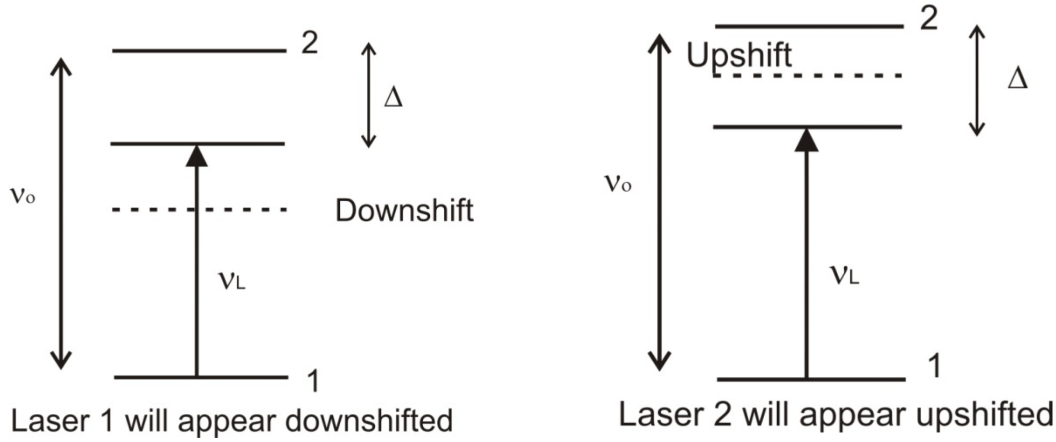
$\tilde{v} \sim 250$ m/s
$v_{rec} \sim 1$cm/s

Need many events to reduce kinetic energy. A limitation is that the Doppler shift will shift atoms out of resonance as the atom slows down.

Two Laser Experiment



Combined effect of radiation pressure force due to 2 lasers can lead to damping Force → F = -αv



Differential absorption → always more absorption from laser opposing motion causing motional damping

6 beam configuration produces $\boxed{F_{Net} = -\alpha v}$ Damping Force

- Result: optical molasses (damped atomic motion analogous to motion in highly viscous fluid)

Atom Trapping – Effect of Interaction of Magnetic Moment of atom in magnetic gradient dB/dz

- effect causing Doppler cooling force to become position dependent
- produces restoring force, F = -kx

$$F_{mag} = -\vec{\nabla}(\mu\cdot\mathbf{B})$$
$$F_{mag} = \mu\, dB/dz \quad (1D)$$

$$\mu = g_F\mu_B m_F \text{ (magnetic moment of atom)}$$

- μ_B is the Bohr magniton
- m_F is the magnetic quantum number
- g_F is the Lande g factor
- for fixed (+ve) dB/dz, F_{mag} attracts moment
  - toward lower field if m is +ve
  - toward higher field if m is -ve

Zeeman Shift

- energy shift at position z = $\mu \frac{dB}{dz} z = \mu_B g_F m_F \left(\frac{dB}{dz}\right) z$
- Frequency shift at position z = $\left(\frac{\mu_B g_F m_F}{\hbar}\right)\left(\frac{dB}{dz}\right) z = \beta z$

  $\omega_{shift} = \beta z$

  Gradient is produced by anti-Helmholtz coil

  - Laser cooling force becomes position dependent for specific polarization of laser beams

The working principle of a MOT will be illustrated using an atom with a simple level structure.