Laser Cooling and Trapping

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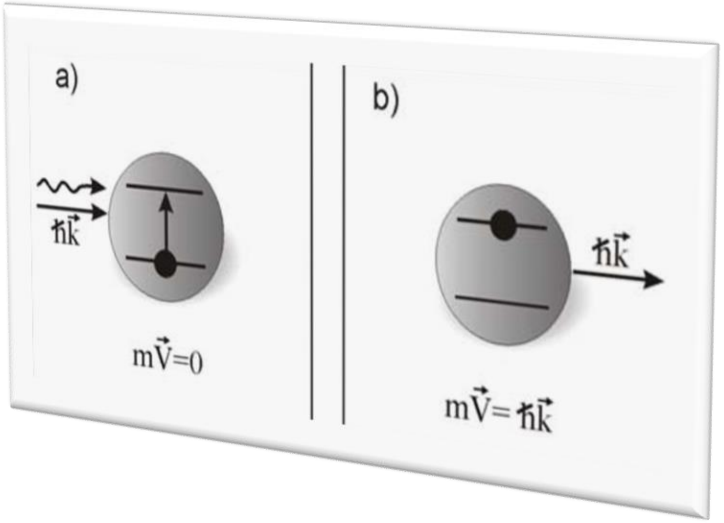
Transfer of momentum between photon and atom

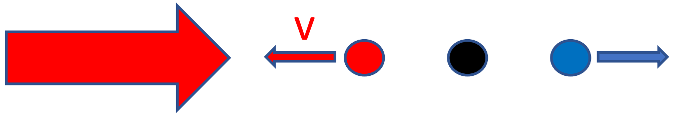
When a photon is absorbed, its momentum is transferred to the atom retaining both its magnitude and direction.

1) For the case, where the atom is at rest



2) For the case, where the atom is in motion

Laser frequency, ω_L< resonance frequency ω_o

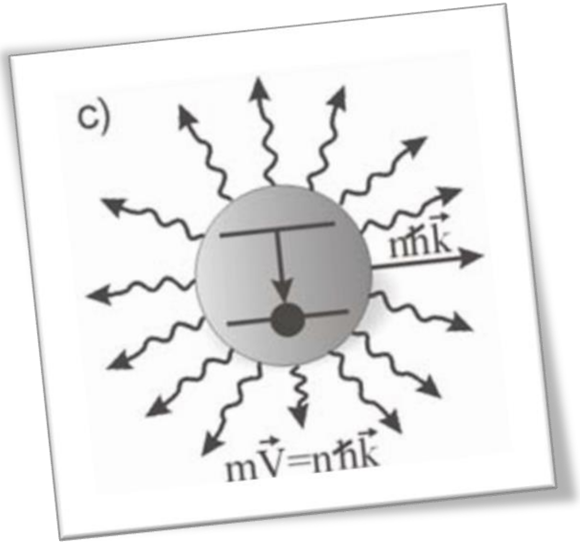


$\omega_L = (1+v/c)\ \omega_o$

Red detuning resonance condition

Effect of Spontaneous Emission

- ✓The photon absorption is followed by spontaneous emission.
- ✓The spontaneous emission is isotropic, thus there is no net change of momentum on average.



- ✓Thus overall, the change of the momentum is solely the effect of absorption and the net force along the direction of laser.

Effect of Stimulated Emission

✓The net force increases with intensity of the incoming light until the stimulated emission begins to play a role, at very high intensity.

✓ The photon emitted by the stimulated emission moves in the same direction as the stimulating photon.

✓So, the momentum transfer in the process of the stimulated emission is directed opposite to the momentum transfer during the absorption.

✓Thus the total change of atomic momentum in such a **sequential** process equals zero.

✓Therefore, the resultant (de/ac)celeration cannot exceed value,

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

https://doi.org/10.1103/PhysRevLett.24.156

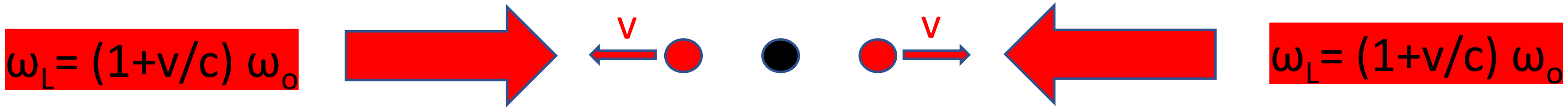
Effect of Stimulated Emission

- ✓With narrow linewidth lasers, the scattering rate of 10^7 s^{-1} or more absorption per second is realistic.
- ✓In such condition, an atom moving in the direction opposite to the photon beam could be decelerated very efficiently.
- ✓Taking typical initial thermal velocity, the time to halt an atom amounts to Δt ~ 1 ms.
- ✓Thus, lasers can provide strong brake action to the moving atoms.

Doppler Cooling and Optical Molasses (OM)

✓The travelling atom sees the Doppler shifted frequency $\omega = \omega_L - \vec{k}\vec{v}$

✓If two weak counter-propagating red-detuned lasers act on the atoms,

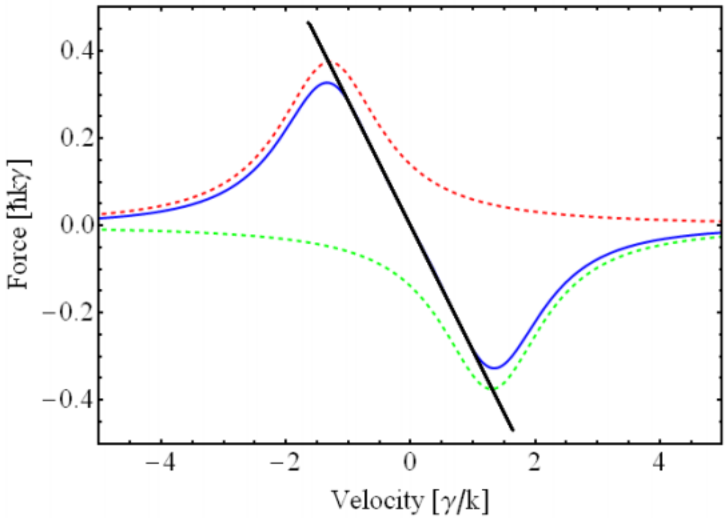


ω_L= (1+v/c) ω_o

ω_L= (1+v/c) ω_o

✓Net force is given by, $\vec{F}_{OM} \cong \dfrac{8\hbar k^2 \delta S \vec{v}}{\gamma[1+S+(2\delta/\gamma)^2]^2}$

$$\boxed{\vec{F}_{OM} \cong -\beta\vec{v}}$$

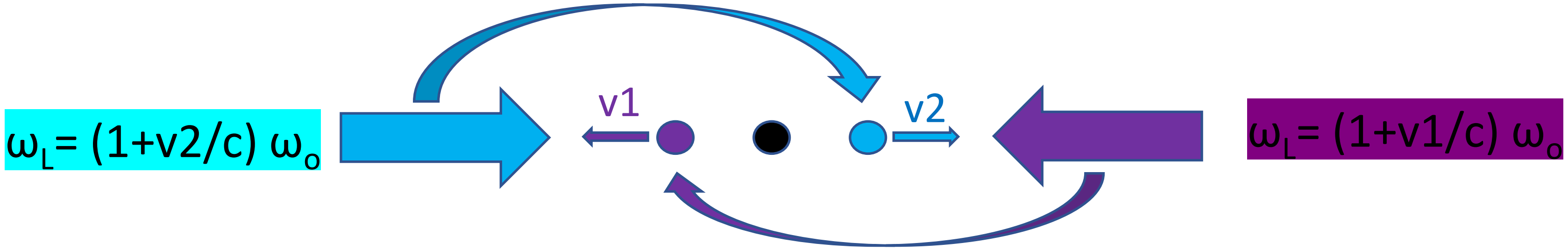


β is the friction parameter.

✓For slow atoms, the force is proportional to the magnitude of the velocity. It resembles a viscous damping.

Why red-detuning and not the blue?

- The principle of cooling is that the resonant radiation pressure/force acts against the spreading direction of atomic velocity.
- Using positive/blue detuning does the opposite and causes heating.
- In other words, the atoms gain energy.



$\omega_L = (1+v2/c)\ \omega_o$

v1

v2

$\omega_L = (1+v1/c)\ \omega_o$

Doppler cooling limit

- ✓ Momentum kicks resulting from photon recoil impose its lower limit which is non-zero.
- ✓ The temperature limit results from an equilibrium between laser cooling and the heating process arising from the random nature of both the absorption and emission of photons.

$$\left(\frac{dE}{dt}\right)_{\text{cooling}} = \vec{F}_{OM}\vec{v} = -\beta\vec{v}^2 \quad = \quad \left(\frac{dE}{dt}\right)_{\text{heating}} = \frac{1}{M}\frac{d}{dt}< p^2 > = \frac{1}{M}\hbar^2k^2\Gamma'_{SC}$$

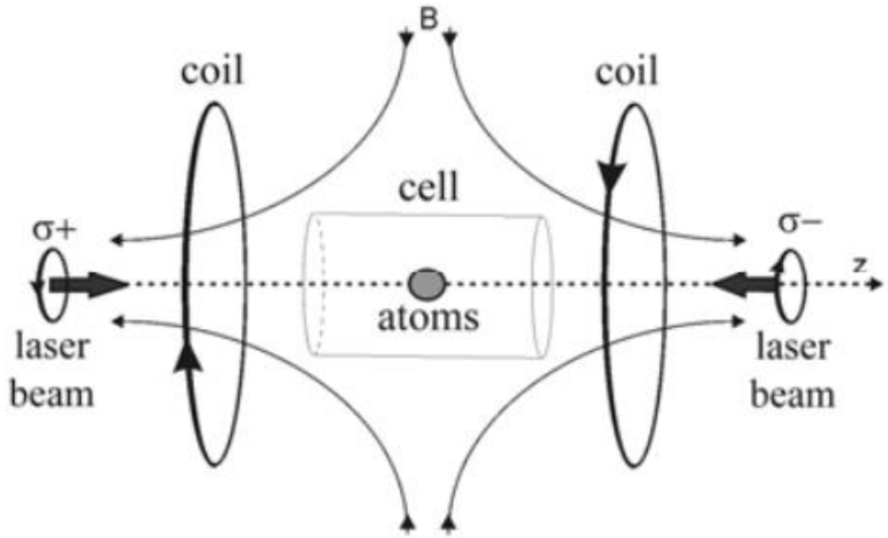
- ✓ Using equipartition theory, convert v^2 term in terms of temperature T.

Doppler limit $$T_D \cong \frac{\hbar\cdot\gamma}{2k_B}$$

T_D depends only on γ – the inverse lifetime (the natural width) of the excited state used in the cooling. Typically, T_D is few 100 μK corresponding to velocities of 10 cm/s.

Introduction of magnets

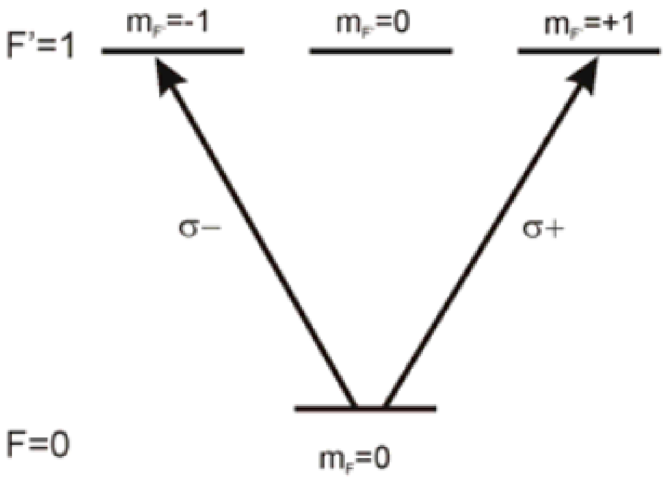
- ✓It should be noted that the resonance radiation pressure force alone is not able to provide stable trapping of atoms. It certainly provides cooling but not trapping.
- ✓Now, we are talking about **Magneto-Optical Trap (MOT).**
- ✓It consists of two laser beams of opposite circular polarization (right σ^+ and left σ^-) counterpropagating along the z-axis.
- ✓ **B** changes linearly with z and its sign alters in the trap center.

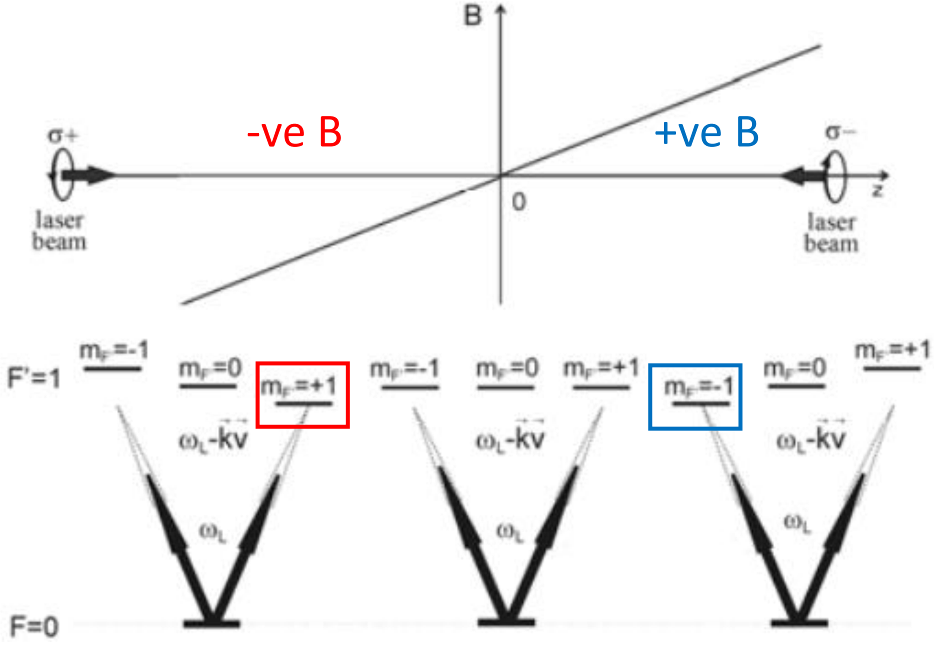


1D model of MOT

Magneto-Optical trap (MOT)

✓The introduction of the magnetic field lifts the degeneracy and splits the hyperfine structure into the sub-levels (Zeeman effect).





Selective absorption of the circularly polarized light

Momentum transfer from σ^+ laser is localized on the left side or negative value of **B** while it is the opposite for σ^-.

As a result, the atom is pushed toward the field free (B = 0) region.

Magneto-Optical trap (MOT)

- ✓When both the Doppler and Zeeman shifts are small compared to the detuning δ, the denominator of the force can be expanded and the result becomes

$$\vec{F}_{MOT} \cong -\beta\vec{v} - \xi\vec{r}$$

where ξ is the spring constant.

- ✓ This force leads to damped harmonic motion of the atoms,

where the damping rate $\Gamma_{MOT} = \beta/m$,

and the oscillation frequency $\omega_{MOT} = \sqrt{\xi/m}$.

- ✓The magnetic effect operates in position space, whereas doppler effect operates in velocity space.
- ✓Since the laser light is detuned below the atomic resonance in both cases, compression and cooling of the atoms is obtained simultaneously in a MOT.

Sub-Doppler Cooling

✓The Doppler limit was considered the the lowest temperature that could be achieved via laser cooling.

✓However in 1988, the temperature of laser cold sodium was measured six times lower then the expected limit. (https://doi.org/10.1103/PhysRevLett.61.169)

✓This new discovery was explained with the specific role that the multi level structure of the atom and the polarization of the light play in the laser cooling.

✓A mechanism that allows temperature below the Doppler limit is the polarization gradient cooling mechanisms:

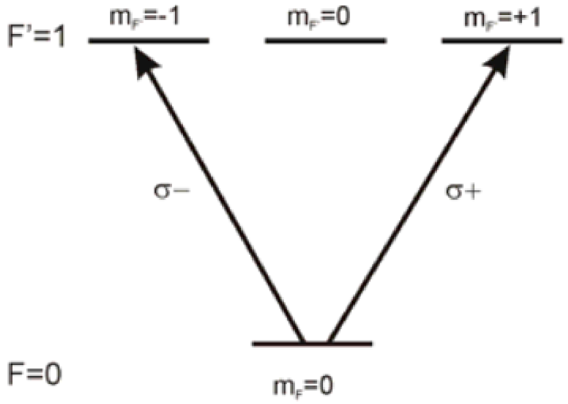
1. Orthogonal linear polarizations (lin ⊥ lin case)
2. Orthogonal circular polarizations (σ^+ σ^- case)

✓Cooling with the polarization gradient is possible only for atoms initially pre-cooled by the Doppler cooling, atoms have to be sufficiently slow.

Orthogonal linear polarizations (lin ⊥ lin case)

✓The atom in a nearly resonant field, aside from absorption, is also subject to light induced shifts of its energy levels known as the ac-Stark shift (also called "**light shift**" in the limits of low intensity light).

✓ Under the influence of the light field the population distribution of the magnetic sublevels of the ground state becomes modified.



✓For z-coordinate where the effective polarization is σ^+ the population is transferred entirely to the $m_F = +1/2$ sublevel, while for σ^- the population is transferred entirely to the $m_F = -1/2$ sublevel.

✓ This process is known as optical pumping.

Orthogonal linear polarizations (lin ⊥ lin case)

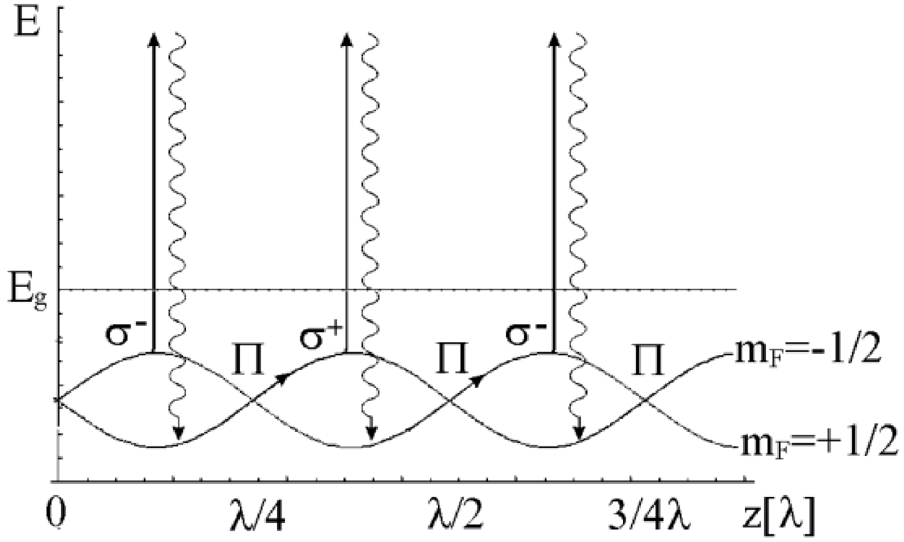
✓As the atom in the $m_F = +1/2$ propagates along z, the potential energy changes along with the polarization:

1. climbs the potential hill at $\lambda/8$ losing its kinetic energy,
2. get excited by σ^- light at the hilltop and,
3. eventually undergoes spontaneous emission to $m_F = -1/2$ level.

✓ The emitted photon carries out more energy than the absorbed one.

✓Thus in a single absorption/emission cycle the atom loses energy equal the light induced splitting between both levels.

✓This mechanism is also called the Sisyphus cooling.



The cooling will be no longer possible when the kinetic energy is lower than the height of the hill.

Orthogonal circular polarizations (σ^+ σ^- case)

- ✓This is the case discussed before as well in the slide “Introduction of magnets”
- ✓It uses the unequal distribution (orientation) of the Zeeman levels while the Doppler cooling utilizes the Doppler shift of the beam frequency.
- ✓The Sisyphus effect is not present.

Sub-Doppler Cooling Limit

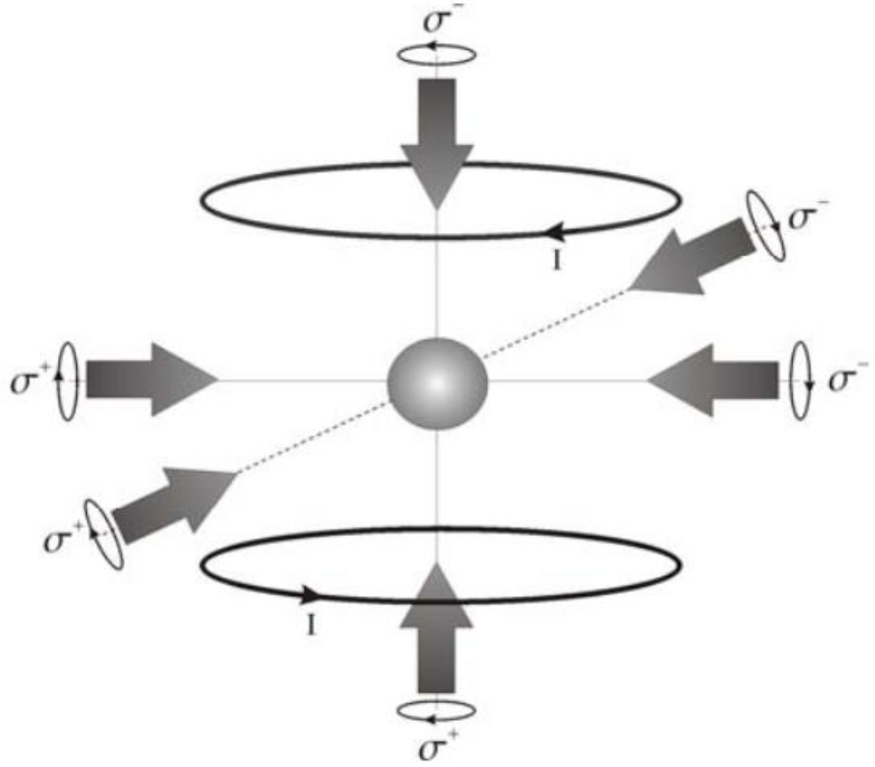
- ✓Both of the above discussed mechanisms can produce the ultra-low temperatures (of the order of few 100 nK) with a characteristic limit related to the recoil momentum.
- ✓This limit is also called the recoil temperature.

$$T_{recoil} = \frac{\hbar^2 k^2}{2Mk_B}$$

- ✓If the intention is to study the Doppler cooling without the interference of the Sisyphus cooling, one can use even isotopes with I = 0.

Realization of the trap

- ✓It is standard to use 6 red-detuned laser beams in a MOT.
- ✓In the presence of an adequate magnetic field, the velocity- and position-dependent forces cause both cooling and confinement of atoms, which become trapped at the B = 0 point.



Realization of the trap

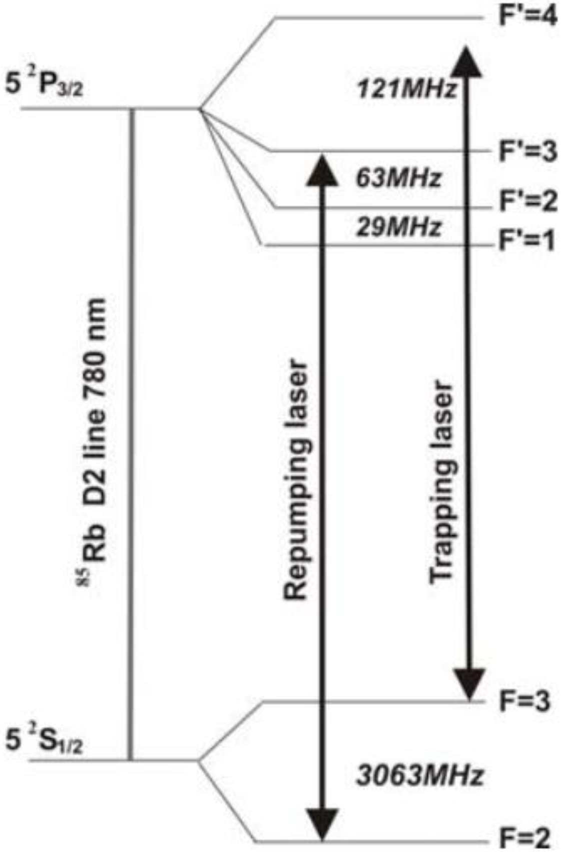
- Why do we need a repumping laser?

✓Considering a Rb trap, the cooling transition is F=3 ⟷ F’=4. The transition is closed and any atom excited to F’=4 will spontaneously return to F=3.

✓However, there is always a possibility of off-resonant excitation of another transition to the F’= 3 level as well. In this case, the decay to F = 2 and F = 3 follows.

✓Eventually, the optical pumping will transfer all available atoms into the F = 2 level. The cooling will become impossible.

✓The repumping laser, resonant with the F = 2→F’= 3 transition serves to return atoms, which leaked to the F = 2 state, back to the trapping cycle.



Limitation of this technique

- ✓In the Magneto optical trap, it is clear that de-tuning is a fundamental parameter that is exploited to cool and trap the atoms.
- ✓We are dealing with detuning less or comparable to the natural line width of the transitions.
- ✓Looking from the Doppler point of view, it constitutes a very small fraction of the total velocity distribution. In other words, we lose a large fraction of atom that goes un-interacted with the resonant lasers.
- ✓In order to avoid this loss, we have to slow down the atoms before arriving to the MOT. Two techniques are employed to maximize the number of atoms that can be cooled.
  1. Frequency Chirping
  2. Zeeman Cooling

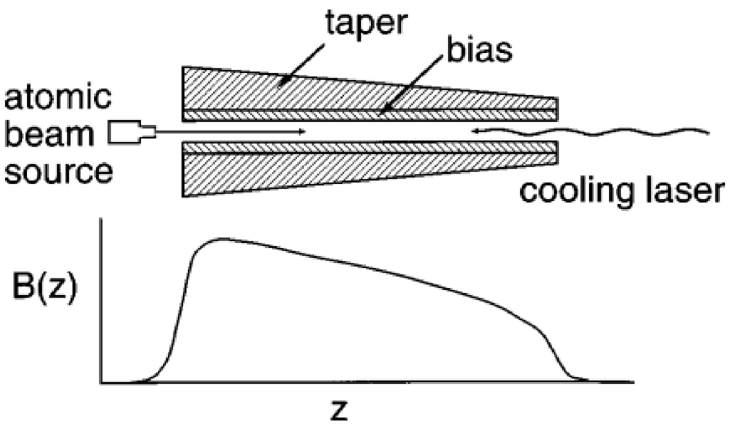
Frequency Chirping and Zeeman Slower

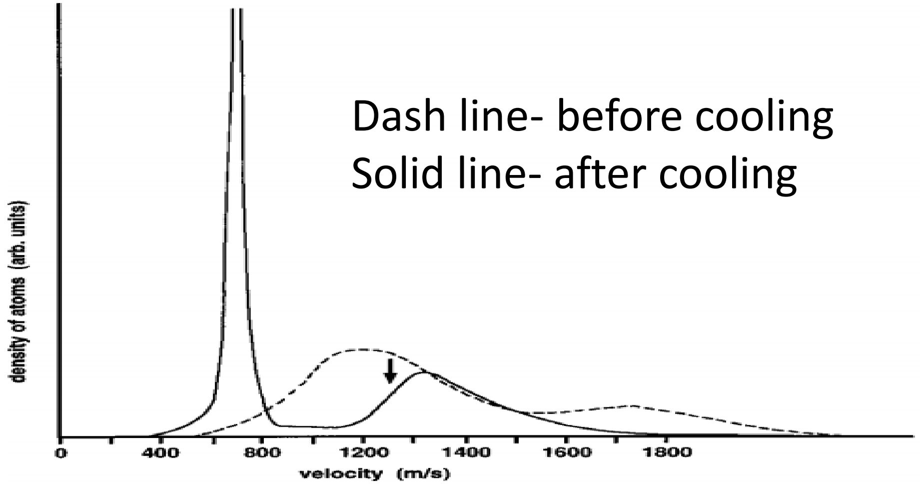
Frequency Chirping:

It is basically modulating the frequency of the resonant laser to tune with the Doppler shifted frequency of most velocities in the distribution.

Zeeman Slower:

The magnetic field is modulated in such a way that the Zeeman splitting continuously balance is out the Doppler detuning as the atoms move through it and get colder.





Dash line- before cooling
Solid line- after cooling

Applications

1. High-resolution spectroscopic measurements
2. Studying the behavior of ultracold gases, which can exhibit interesting phenomena such as Bose–Einstein condensation (BEC)
3. Ultraprecise measurement of gravitational fields, based on the Doppler shift of free-falling cooled atoms, on Bloch oscillations
4. Lithography with cold atomic beams to form very accurately controlled structures

etc……..

Next step: trapping neutral molecules

- ✓**Indirect approach**
  - ✓Produce precool atomic gases before associating pairs of atoms into ultracold molecules.
  - ✓However, this approach is restricted to molecules composed of atomic species that can be laser cooled and, as yet only diatomic species made of combinations of alkali atoms have been produced this way.
- ✓**Direct approach**
  - ✓Cools the molecule of interest itself and so must tame the complex internal structure of a given molecule.
  - ✓Covers a wide array of experimental techniques and provides access to a diverse range of molecular species with different properties and internal structures.

Challenges in laser cooling molecules

✓The same rich internal structure that make molecules useful for a wide range of applications also poses challenges once believed to be fatal to any attempt at laser cooling.

✓Nevertheless, over the past several years, however, a subset of molecules has been identified that are accessible to laser cooling and multiple groups have now begun to extend laser cooling and trapping techniques from atoms to molecules.

✓Some molecules have been successfully laser trapped e.g. SrF, CaF ,YO, YbF (https://doi.org/10.1088/1361-6455/aadfba (2018))

Thank you