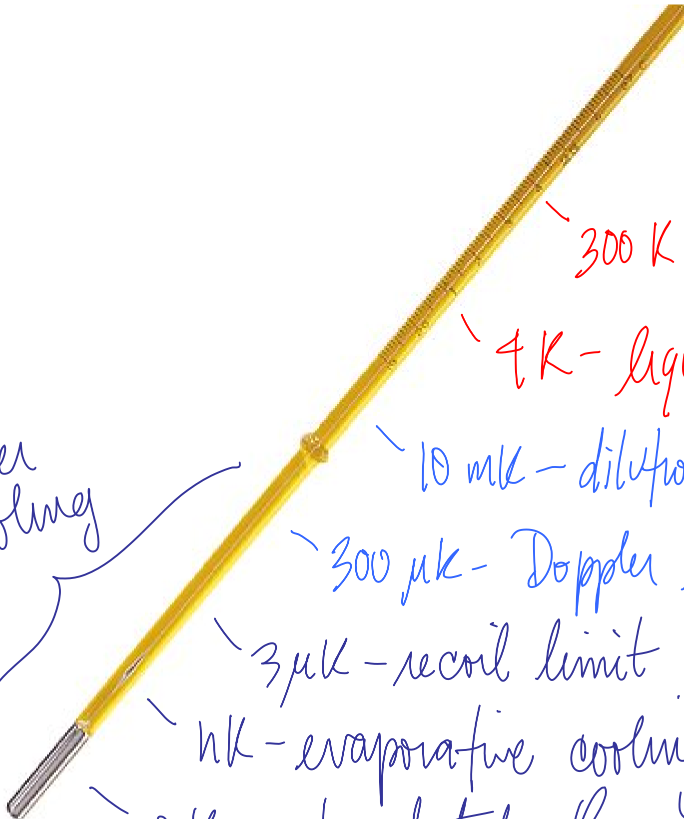
Laser cooling

Note Title 4/6/2005



300 K – room temperature

4 K – liquid Helium

10 mK – dilution refrigerator

300 μK – Doppler limit

3 μK – recoil limit

nK – evaporative cooling

0 K – stimulated Raman cooling (ion traps)

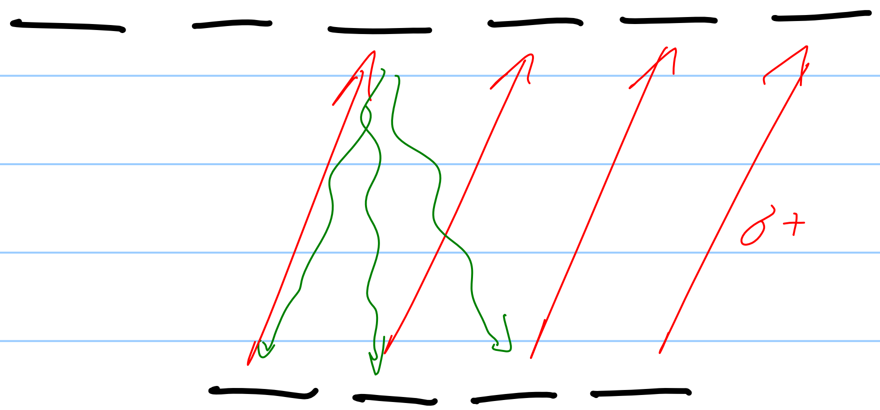
laser cooling

He-buffer gas cooling can also work in this range (see H BEC by Kleppner)

There are fancy quantum calculations which describe laser cooling, but simple arguments get us most of the physics!...

One thing that's good to know about is optical pumping.

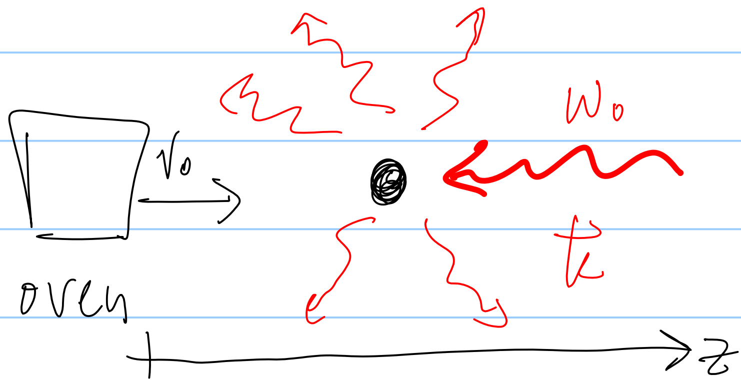
There's all different versions of optical pumping, but the basic idea is always the same:



even if decay w/ $\sigma^\pm, \pi$ is possible, the population will eventually move to the "right"

Simplest version of laser cooling: Doppler cooling and optical molasses

The scattering force can be used to slow an atomic beam:



Each photon transfers momentum $\hbar k$ to the atom on absorption, and the atom radiates this away in all directions, leading to an average transfer of $\hbar k$ per scattering event

$$F_{scatt} = \hbar k \underbrace{\frac{\Gamma}{2} \frac{s}{1+s+4\left(\delta/\Gamma\right)^2}}_{\text{scattering rate}} = \frac{dp}{dt}$$

$\delta = \omega - \omega_0 + kv$ detuning depends on velocity

PROBLEM: scattering rate changes drastically as the velocity slows (δ changes)

SOLUTION: Compensate with the Zeeman effect!

for constant deceleration: $v = v_0\left(1 - z/L_0\right)$
(L_0 is stopping distance)

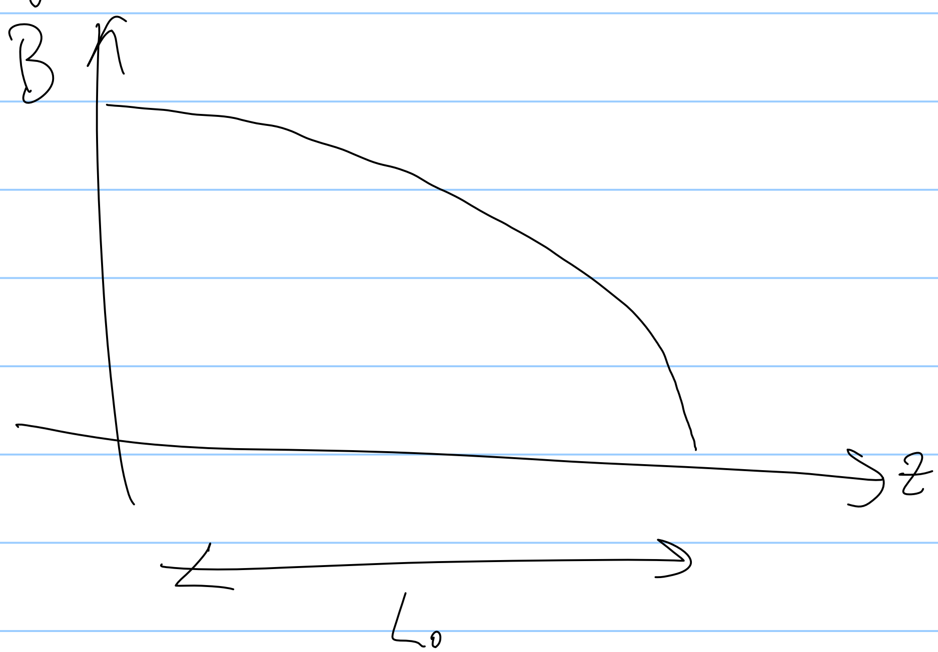
we need $\quad \omega + kv - \left(\omega_0 + \frac{\mu B}{\hbar}\right) = \delta$ constant

this is handled in various ways
(lots of experimental complication)

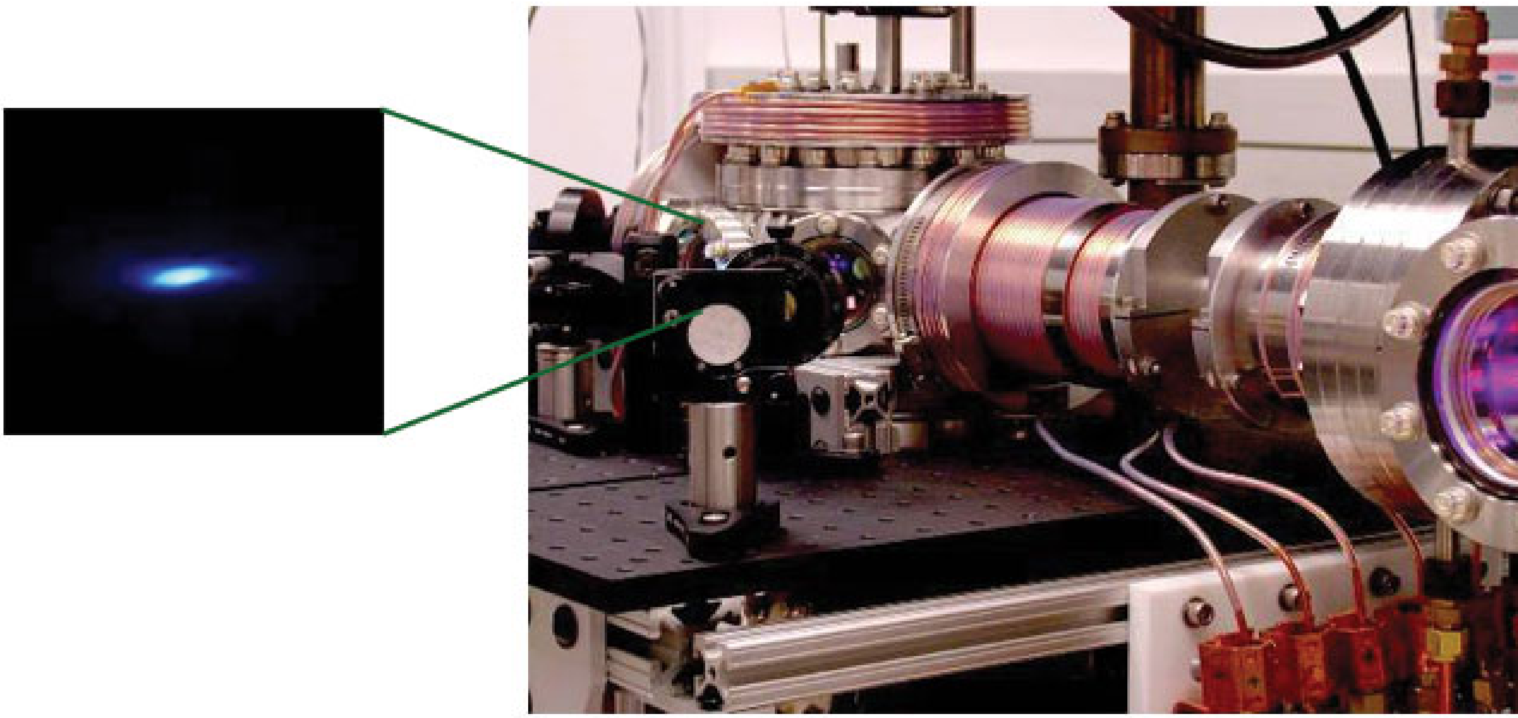
ex:

$B = B_0 \sqrt{1 - z/L_0}$

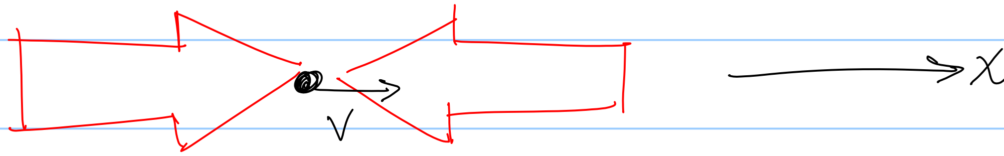
$B_0 = \frac{\hbar v_0}{\lambda \mu}$



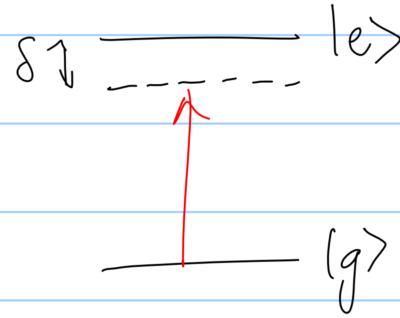
NIST Erbium slower and MOT



Optical molasses

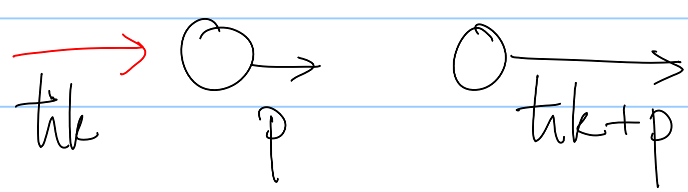


two laser beams, detuned red from an atomic resonance



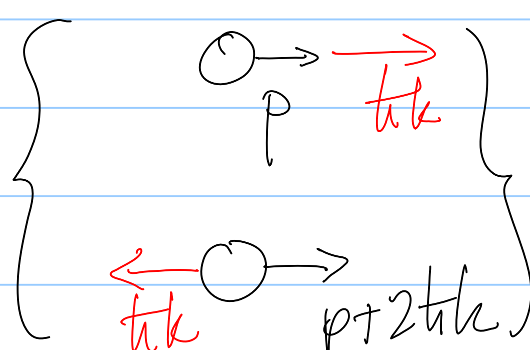
As far as the atom is concerned, the light is Doppler shifted: $\Delta\omega = -\vec{k}\cdot\vec{v}$

Every time the atom scatters, it recoils:



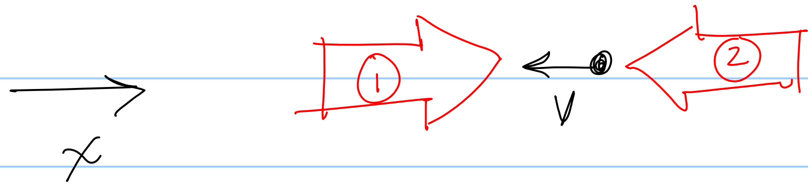
absorption

re-emission — random direction

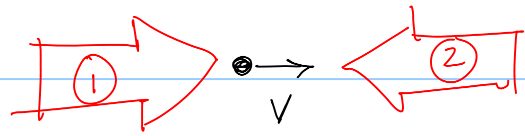


— on average — the total recoil is $\hbar k$

So, the force on the atom is $\Delta p \cdot R$, where R is the scattering rate. Here's the tricky thing:



beam ① is blue-shifted, so the scattering rate is increased compared to ② — net force in $+\hat{x}$



exact opposite is true — net force in $-\hat{x}$ direction

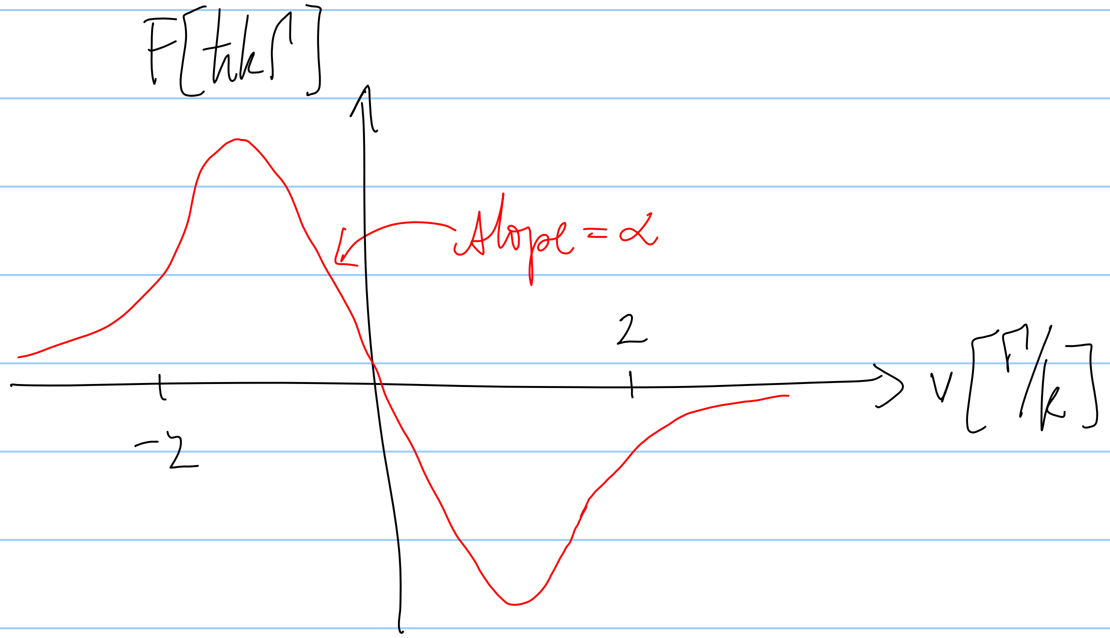
So, we have a velocity-dependent force — like friction!
Note: spontaneous emission is a requirement for any laser cooling — that's where the entropy goes. A simple model:

$$\vec{F} = \vec{F}_+ + \vec{F}_-$$

$$\vec{F}_\pm = \pm \underbrace{\hbar \vec{k}}_{\Delta \vec{p}} \underbrace{\frac{\Gamma}{2} \frac{s}{1+s+4\left(\frac{\delta \mp |\vec{k}\cdot\vec{v}|}{\Gamma}\right)^2}}_{\text{rate}}$$

$$\vec{F} \simeq \frac{8\hbar k^2 \delta s \vec{v}}{\Gamma\left[1+s+\left(\frac{2\delta}{\Gamma}\right)^2\right]^2} + \mathcal{O}\left(\frac{kv}{\Gamma}\right)^4 \equiv -\alpha\vec{v}$$

<u>for $\delta<0$:</u>



To understand how this force leads to cooling, consider:

$$\frac{d}{dt}\left(\tfrac{1}{2}m\bar{v}^2\right) = mv\,\frac{d\bar{v}}{dt} = v\left(m\frac{d\bar{v}}{dt}\right) = \bar{v}F = -\alpha\bar{v}^2$$

where $\bar{v}$ is the average velocity in the gas

equipartition theorem: $\frac{1}{2}m\bar{v}^2 = \frac{1}{2}k_BT$

so, $\frac{d}{dt}\left(\tfrac{1}{2}m\bar{v}^2\right) = k_B\frac{dT}{dt} = -\alpha\bar{v}^2 = -\alpha\frac{k_BT}{m}$

or: $\frac{dT}{dt} = -\frac{\alpha}{m}T$ cooling!

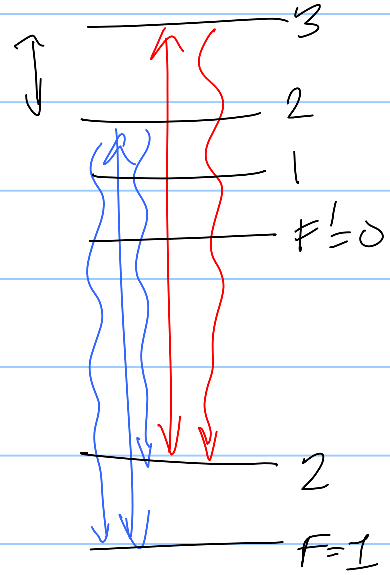
Note that the cooling power falls off rapidly for $v > \Gamma/k$, which is something like 5 m/s.

Doppler cooling 1st demonstrated using trapped ions (Wineland), and is easy to implement in 3-D.

In order for this to work well, you need a "cycling" transition.

In alkalis: ex ^{87}Rb

~200 MHz



About 1 out of $\left(\frac{200}{6}\right)^2 \approx 1000$ photons cause a $2 \to 2'$ transition

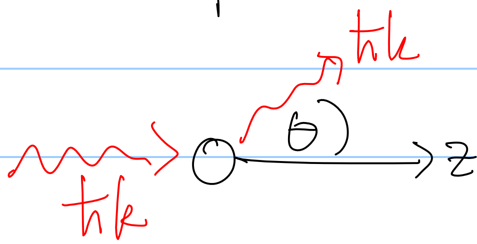
$F'=3 \to F=1$ not allowed!

← off-resonant scattering to $F'=2$ will populate this level – so we need a "repumper"

So, now the atoms cool to $T=0$ right? Not! The random recoil process is a competing heating process.

Recoil is a random process that leads to diffusion in momentum distribution...

Consider absorption and re-emission of photons:



conservation of momentum:

$$v_z + \hbar k = \hbar k \cos\theta + v_z'$$

$$\Delta v_z = v_z' - v_z = \hbar k (1 - \cos\theta)$$

If we average over the scattered photon direction θ:

$$\langle \Delta v_z^2 \rangle_\Omega = \left(\frac{\hbar k}{m}\right)^2 \int (1-\cos\theta)^2 d\Omega / 4\pi = \left(\frac{\hbar k}{m}\right)^2 \frac{1}{2} \int_{-1}^{1} d(\cos\theta) (1-\cos\theta)^2 =$$

$$\left(\frac{\hbar k}{m}\right)^2 \frac{1}{2} \cdot 4/3 = 2/3 \left(\frac{\hbar k}{m}\right)^2 = \frac{4}{3} m \frac{\hbar^2 k^2}{2m} = \frac{4}{3} m \cdot E_R$$

where $E_R = \frac{\hbar^2 k^2}{2m}$ is the recoil energy

for a pair of beams, $\frac{1}{2} m \frac{d\langle v_z^2 \rangle_\Omega}{dt} = \frac{1}{2} \, 4/3 \, E_R \cdot 2R = 4/3 \, E_R R$

for 3 pairs of beams: $\frac{1}{2} m \frac{d\langle v_z^2 \rangle_\Omega}{dt} = 4 E_R \cdot R$

so: $\frac{1}{2} m \frac{d\langle \bar{v}_z^2 \rangle_\theta}{dt} = 4 R E_R - \alpha \bar{v}_z^2$ when we consider Doppler cooling and recoil heating

in equilibrium: $\frac{d\langle \bar{v}_z^2 \rangle_\theta}{dt} = 0$

$$\bar{v}_z^2 = \frac{4 E_R R}{\alpha}$$

if we ignore saturation effects:

$$\alpha = \frac{8\hbar k^2 |\delta|}{\Gamma\left[1+\left(\frac{2\delta}{\Gamma}\right)^2\right]^2} \, I/I_{sat} \qquad R = \frac{\Gamma}{2} \, I/I_{sat} \, \frac{1}{1+\left(2\delta/\Gamma\right)^2}$$

then:

$$\bar{v}_z^2 = \frac{\hbar}{m} \, \Gamma/4 \, \frac{\Gamma}{2|\delta|}\left[1+\left(\frac{2\delta}{\Gamma}\right)^2\right]$$

using equipartition: $\frac{1}{2} m \bar{v}_z^2 = \frac{1}{2} kT$

$$T = m\bar{v}_z^2/k_B$$

and: $$T = \frac{\hbar\Gamma}{4k_B} \, \frac{1+\left(2\delta/\Gamma\right)^2}{2|\delta|/\Gamma}$$

this has a minimum value at $\delta = -\Gamma/2$

which is: $T_D = \frac{\hbar\Gamma}{2k_B}$ "Doppler limit"

in Na, $T_D = 240\,\mu K$

In atoms with narrow (i.e., small Γ) transitions, T_D can be smaller than $1\,\mu K$!

Experiments

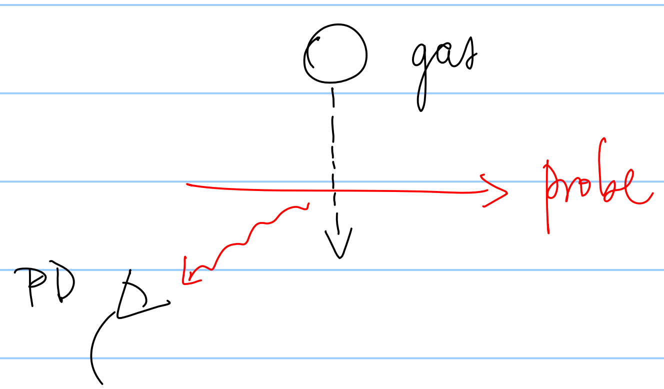
1978 – ion trap – Wineland

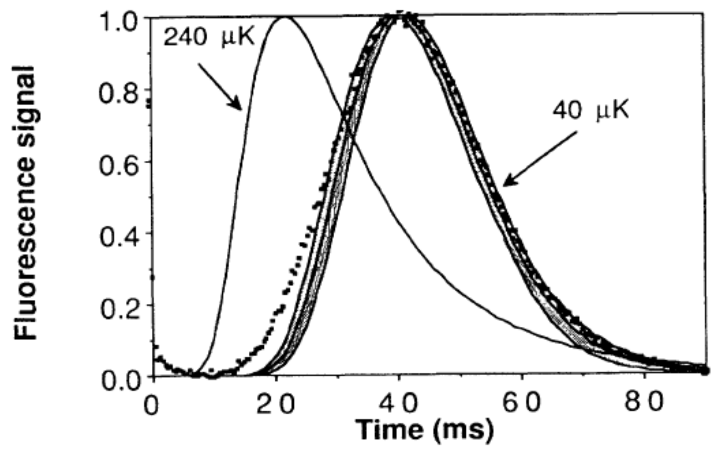
1985 – 3-D molasses – Chu et al

– temperature measurements ~ T_D

1988 – 3-D molasses, Na atoms

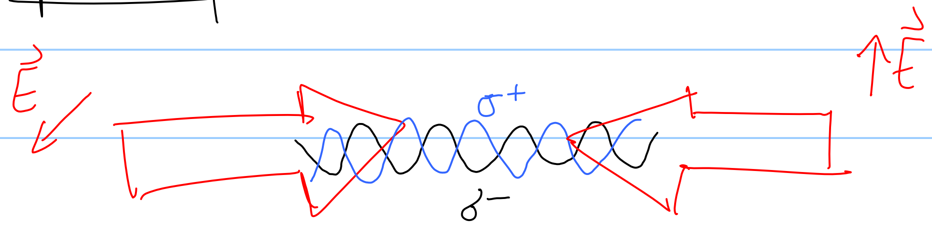
– better temperature measurements – 40 μK!





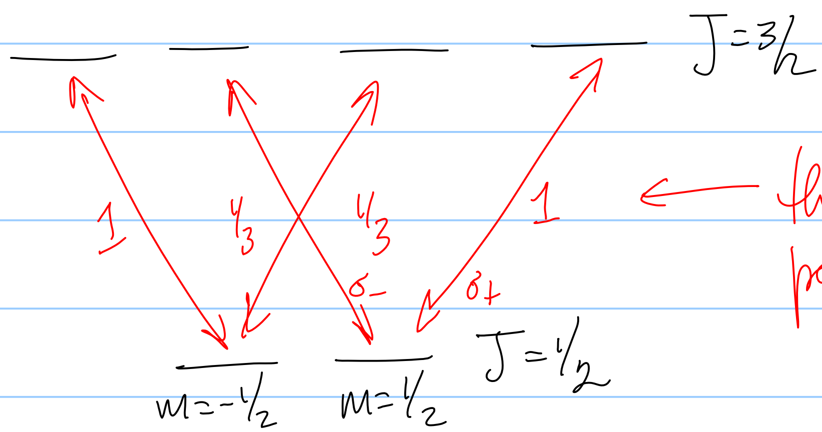
$\boxed{\text{What the fuck?!?!}}$

→ New theory of polarization gradient cooling (Dalibard & Cohen-Tannoudji and others) simplest picture:



lin ⊥ lin configuration

$J = 1/2 \leftrightarrow 3/2$ transition



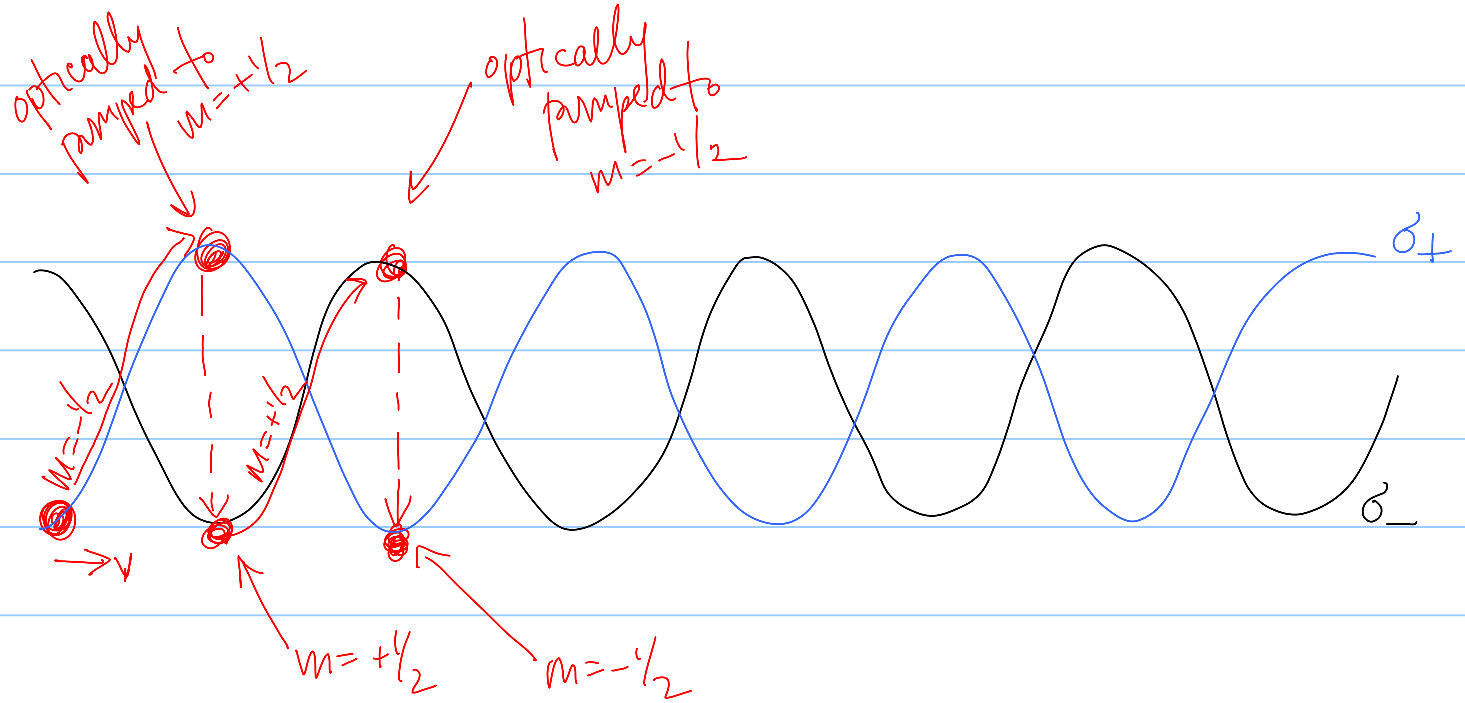
the angular momentum part of $|\langle g|\hat{\varepsilon}\cdot\vec{r}|e\rangle|^2$

So: $m = \pm 1/2$ more strongly coupled to $\sigma\pm$ light

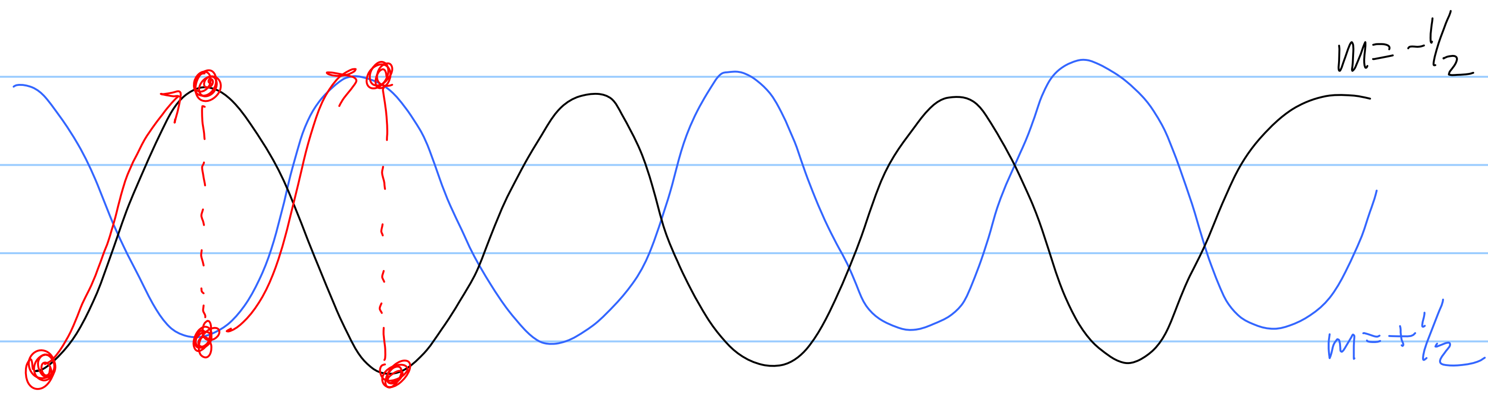
For $\delta < 0$ (red detuning), cooling occurs because of the interplay of the light shifts and optical pumping.

(Remember $\Delta E \propto 1/\delta$)

Intensity:



Light shift (energy)



energy is lost! for large detuning, $\Delta E \sim \hbar \frac{\Gamma^2 s}{4\delta}$ just $|\Omega|^2$

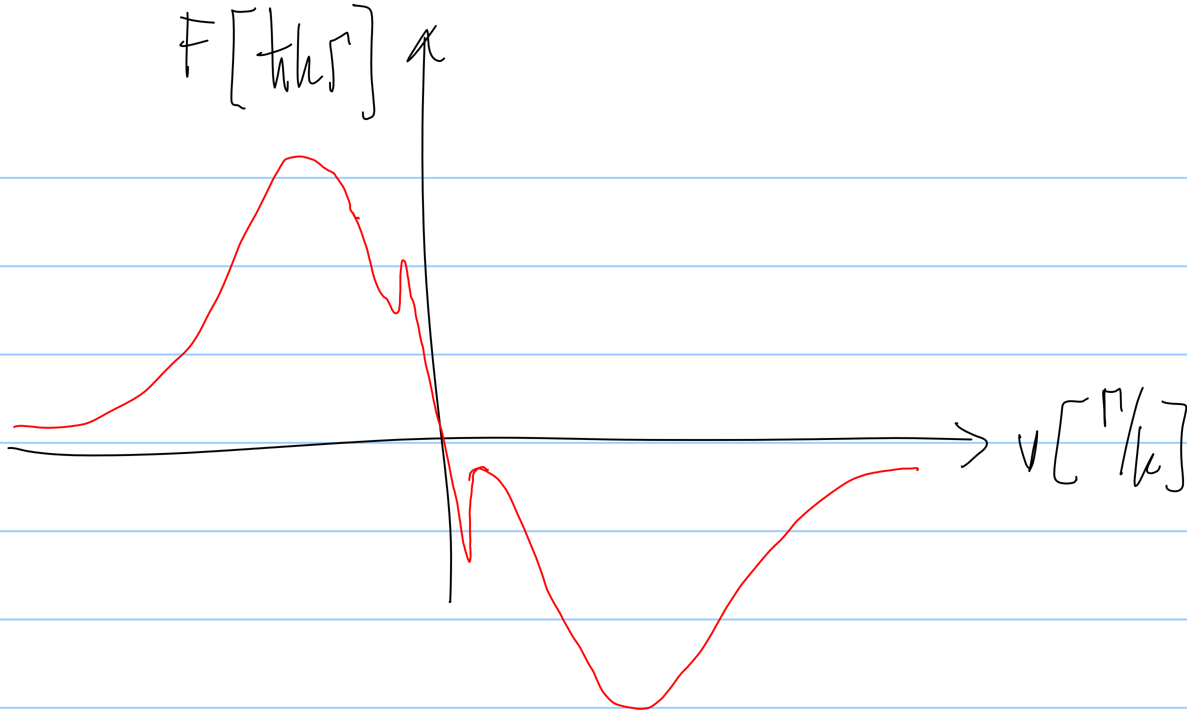
We call this "Sisyphus cooling." Entropy is again leaving through spontaneous emission (specifically spontaneous Raman scattering).

This force only takes over at small velocities:

$v \sim \frac{R}{k}$ ← opt. pumping rate ← length scale over which the pol changes

(the spin has to change on the same length scale as the polarization)

The friction force can be larger than for Doppler cooling at large detunings!

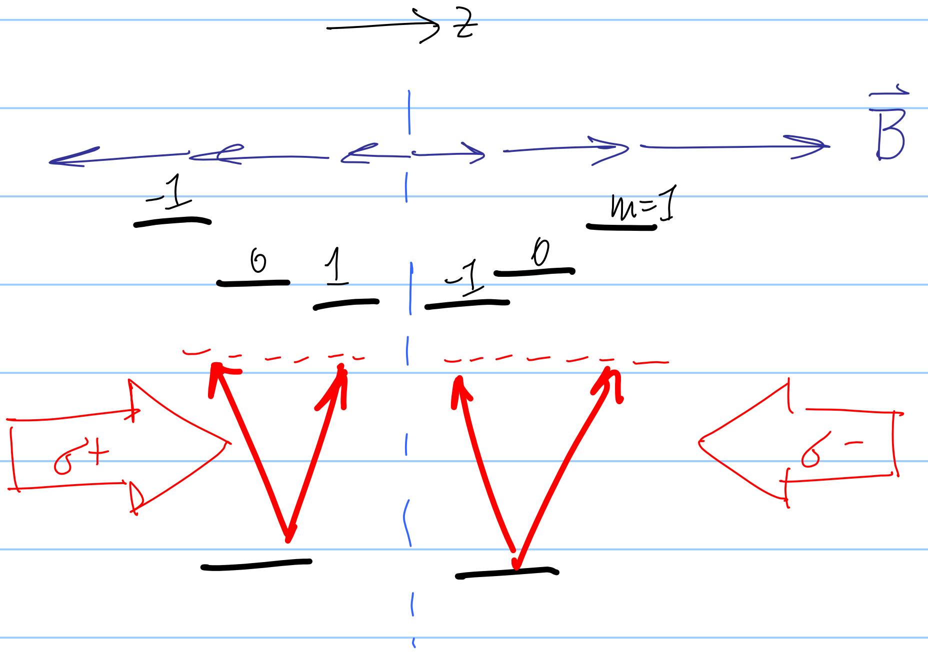


With larger α, the temperature limit is lower (closer to recoil limit) – can see a few μK in Cs (about 10× recoil limit)

Magneto-optic Trap (MOT)

- basic starting point for ultra-cold atom gas experiments
- magnetic field gradient added to 3-D optical molasses to make the optical force spatially dependent

- simplest models are 1-D, $J=0 \leftrightarrow 1$



+ a real MOT works nothing like this!

first demonstrated by Pritchard (1987)

$$\vec{F} = \vec{F}_+ + \vec{F}_-$$

$$\vec{F}_\pm = \pm \frac{\hbar k \Gamma}{2} \frac{s}{1 + s + \left(\frac{2\delta_\pm}{\Gamma}\right)^2}$$

$$\delta_\pm = \delta \mp \vec{k}\cdot\vec{v} \pm \mu' B/\hbar$$

detuning now involves Zeeman shift

Can be written as: $\vec{F} = -\alpha \vec{v} - K \vec{r}$

$$K = \frac{\mu' A}{\hbar k} \alpha$$

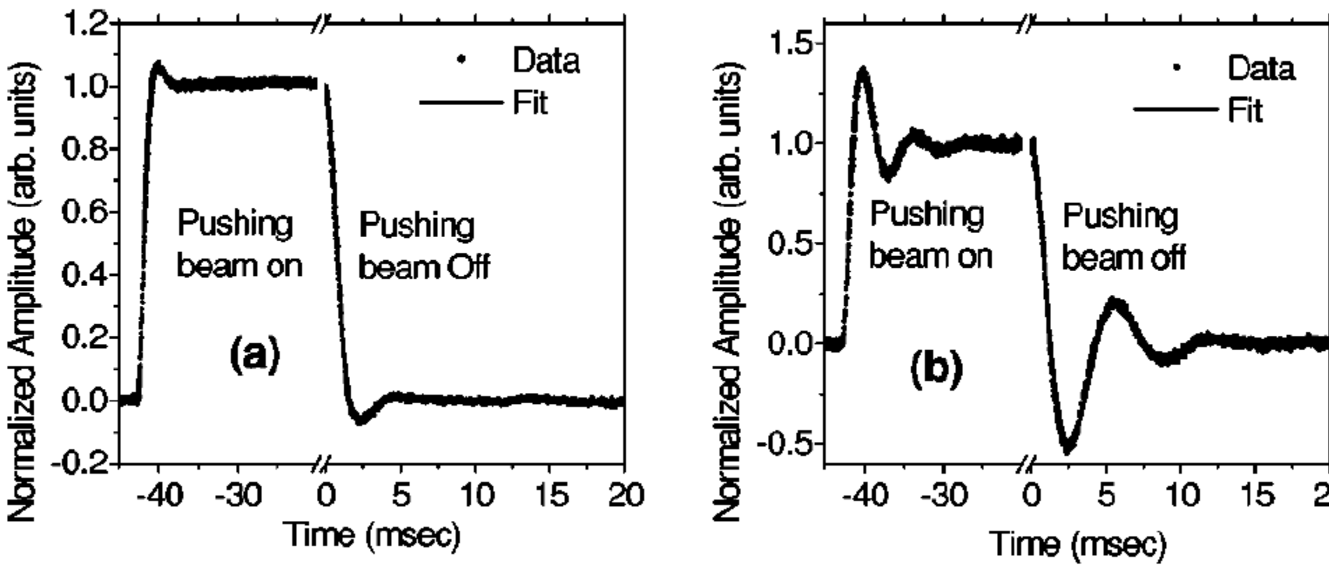
where A is the magnetic field gradient

Typically: $\sqrt{\frac{K}{M}} \sim$ few kHz (w/ $A \sim 10$ G/cm)

$\frac{\beta}{M} \sim$ few hundred kHz

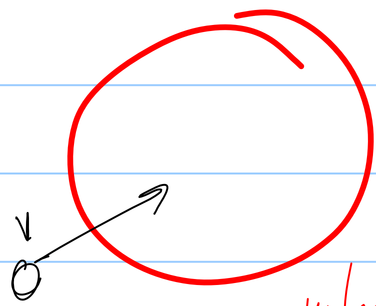
This has been measured!

— See PRA 66, 011401(R) (2002) for something recent with ^{88}Sr atoms



— data at different detunings from Jun Ye's group

Atoms are collected from the "low energy tail" of the room-temperature thermal distribution



intersection of MOT beams

we define a "capture velocity" – max v for which atom is stopped within the beam diameter

Numerical simulations (1-D, Metcalf):

(Na atoms, $\delta = -30$ MHz, $s = 10$)