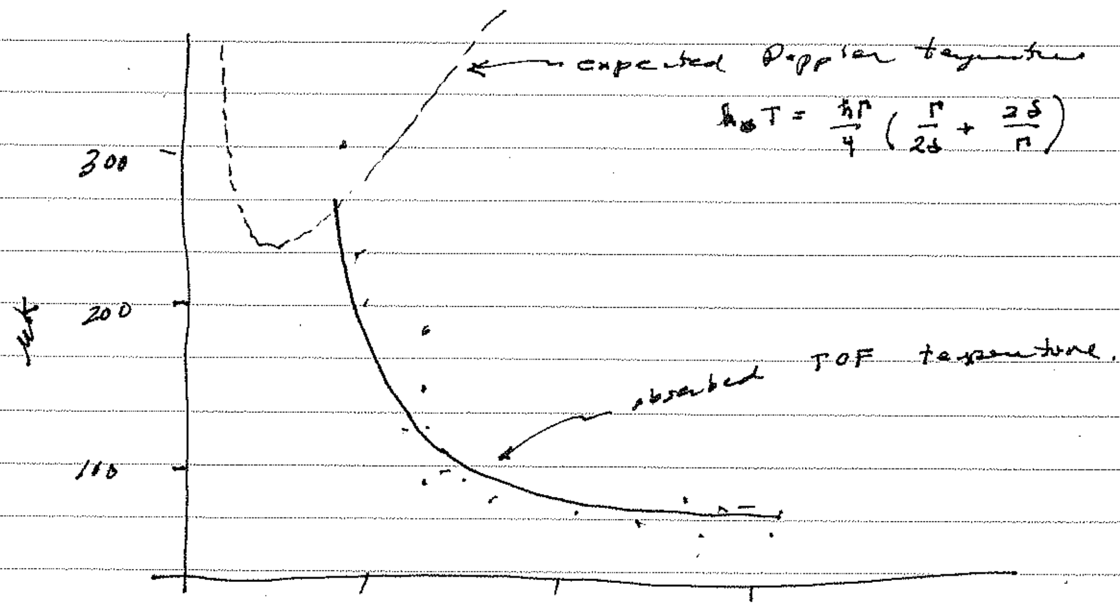
8 December 2005 Sub-Doppler laser cooling continued

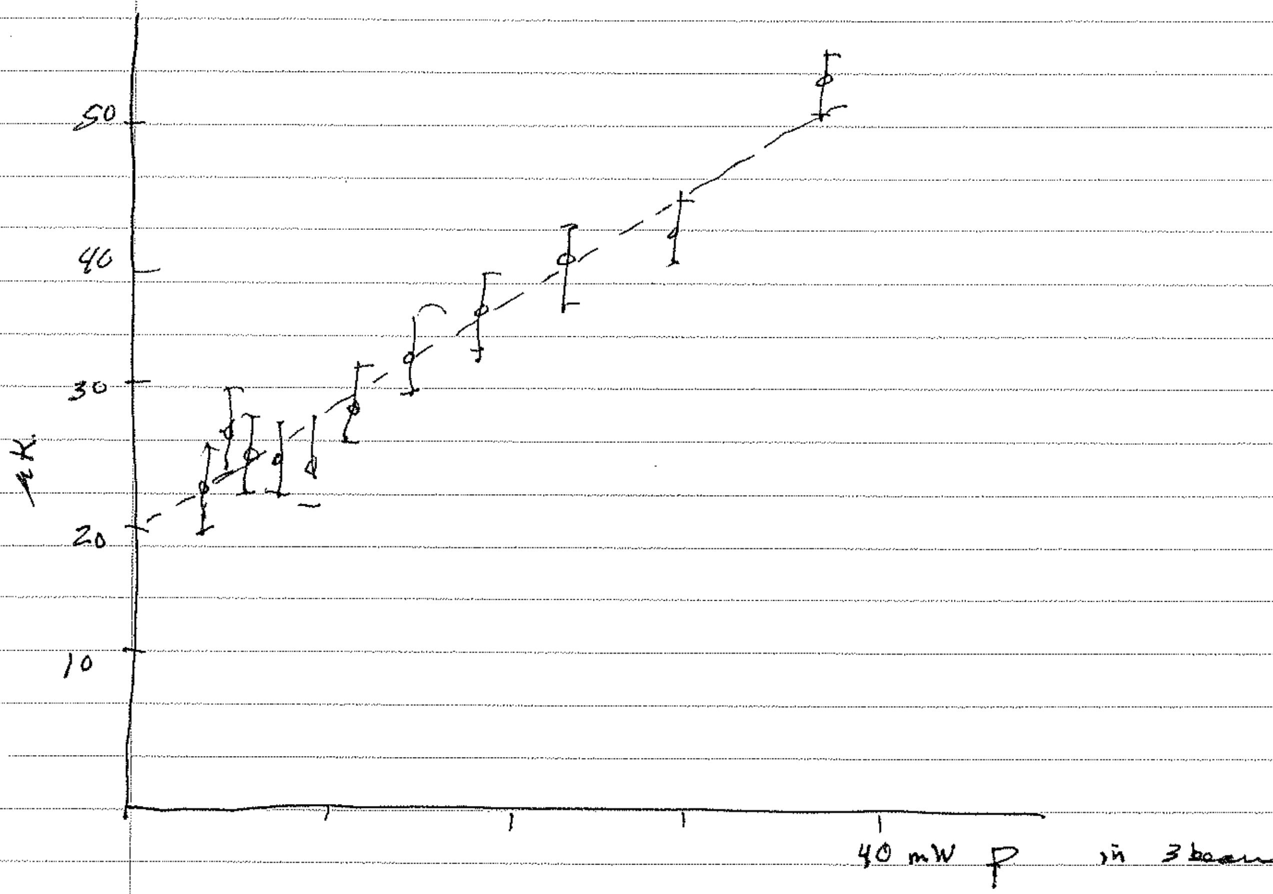
The sub-Doppler temperature seen with time-of-flight was confirmed by three other methods

The temperature depended on detuning in a way different from prediction of Doppler cooling



Also: the temperature went up dramatically when a small magnetic field was applied, even when

$$\Delta\omega_{Zeeman} \ll \Gamma$$



The temperature was linearly dependent on the Intensity.

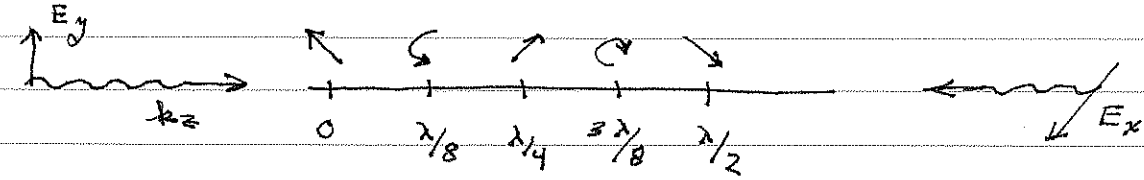
What is going on? Doppler cooling theory is simple! How can it be wrong?

hint: Magnetic field dependence suggest Magnetic sublevels are involved.

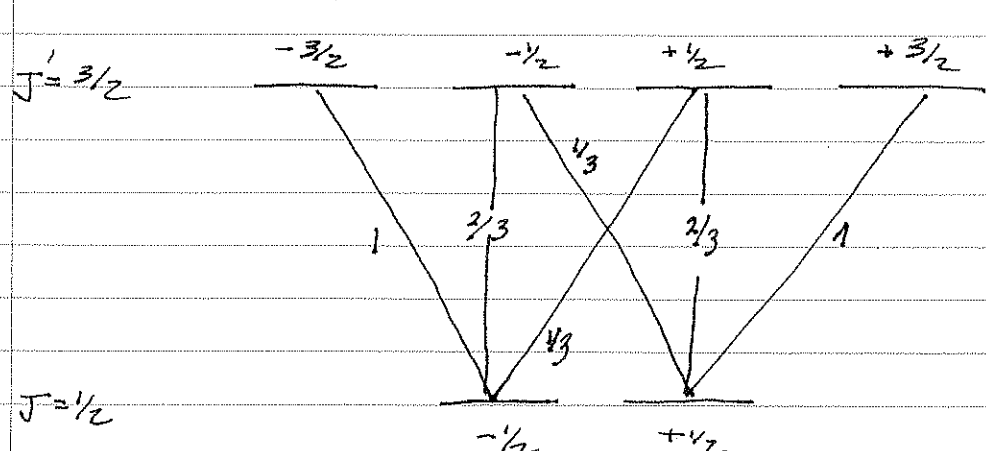
The answer (from Paris - ENS) involved:

- Multilevel atoms
- optical pumping among the sub-levels.
- differential light shifts
- polarization gradient of the light.

polarization gradient

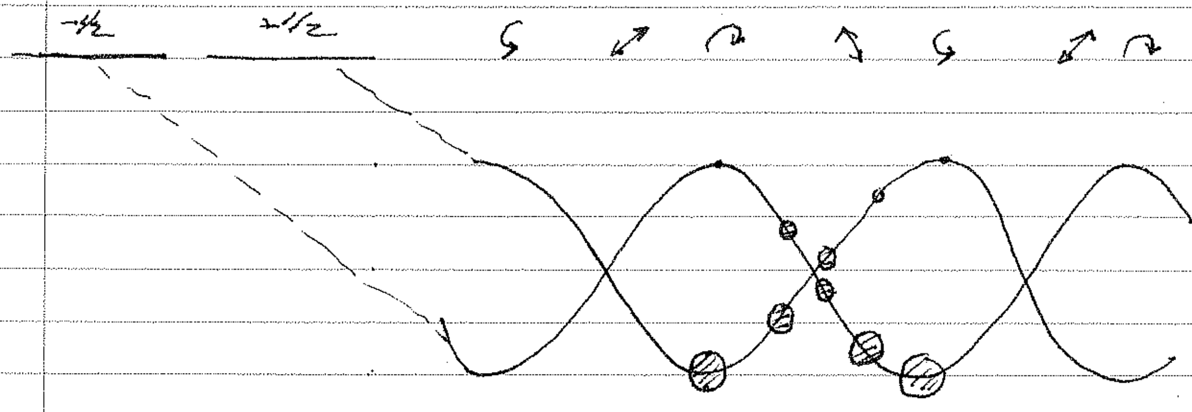


transition strengths



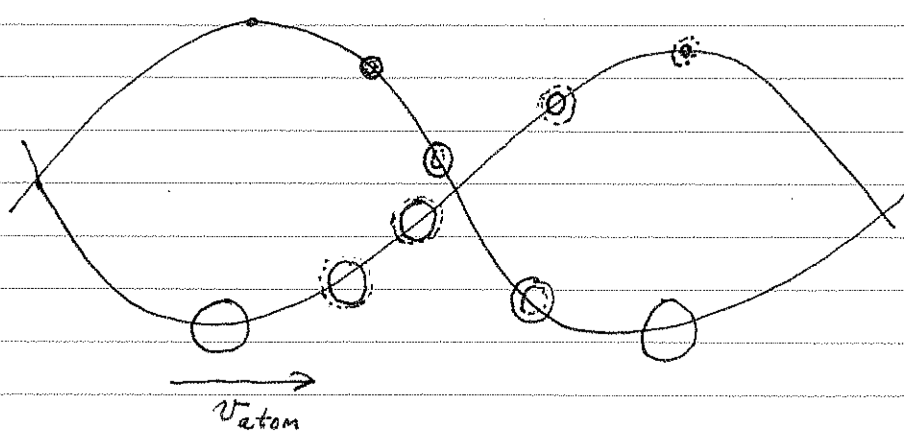
squares of Clebsch-Gordan coefficients

light shifts



atoms pump to the lowest level (when $\delta < 0$ for negative light shift) — populations for static atoms.

When atoms move, populations lag because pumping takes time — longer time for low intensity and large detuning

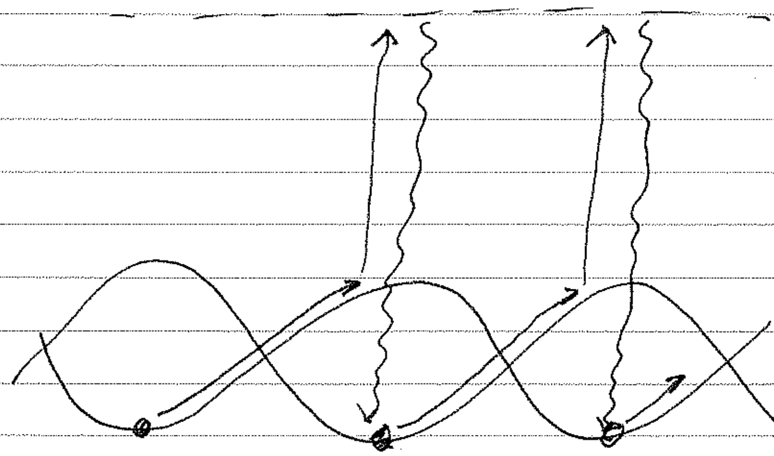


population is larger going up

smaller going down

net result is slowing of atom

Simplified picture:

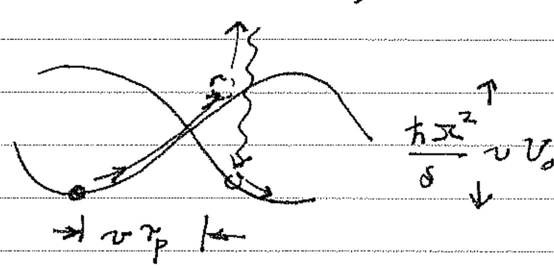


atom pumps after τ_p, where

$$\tau_p^{-1} \sim \frac{\Gamma}{2} \frac{I/I_0}{1+(2\delta/\Gamma)^2} \qquad \text{for } I/I_0 \ll 1$$

$$\text{or} \quad \tau_p \sim \Gamma \frac{\Omega^2/\Gamma^2}{\delta^2/\Gamma^2} \sim \frac{\Gamma\Omega^2}{\delta^2} \qquad \text{for } \delta \gg \Gamma,\ I/I_0 \ll 1$$

handwaving calculation of average force:



$$\langle F \rangle \sim U_0 \left(\frac{v\tau_p}{\lambda}\right)\frac{1}{\lambda} \quad \propto \quad \frac{\hbar\Omega^2}{\delta}\frac{k^2 v}{\Gamma\Omega^2/\delta^2} = \sim \hbar k^2 \frac{\delta}{\Gamma} v$$

total potential

fraction of potential used

characteristic distance over which potential changes

compare to

$$F_{dop}^{max} = \frac{\hbar k^2}{4} v$$

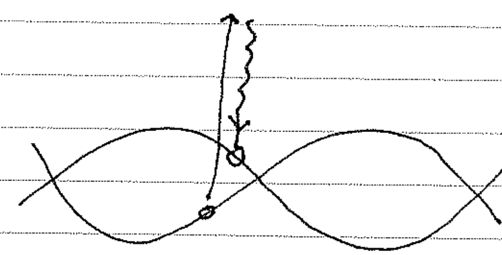
Force is independent of Ω^2, and much bigger than F_{Dopp} for $\delta >> \Gamma$.

This larger friction explains the odd behavior of molasses lifetime.

What about temperature? What about $\Omega^2 \to 0$?

what is the heating? – momentum diffusion.

recall. $k_B T = \dfrac{\mathcal{D}_p}{\alpha}$



$$2\mathcal{D}_p = \langle \dot{p}^2 \rangle$$

$$\mathcal{D}_p \sim \big(\underbrace{F \cdot \tau_p}_{\text{impulse on one potential}}\big)^2 \underbrace{\frac{1}{\tau_p}}_{\text{rate of impulses}}$$

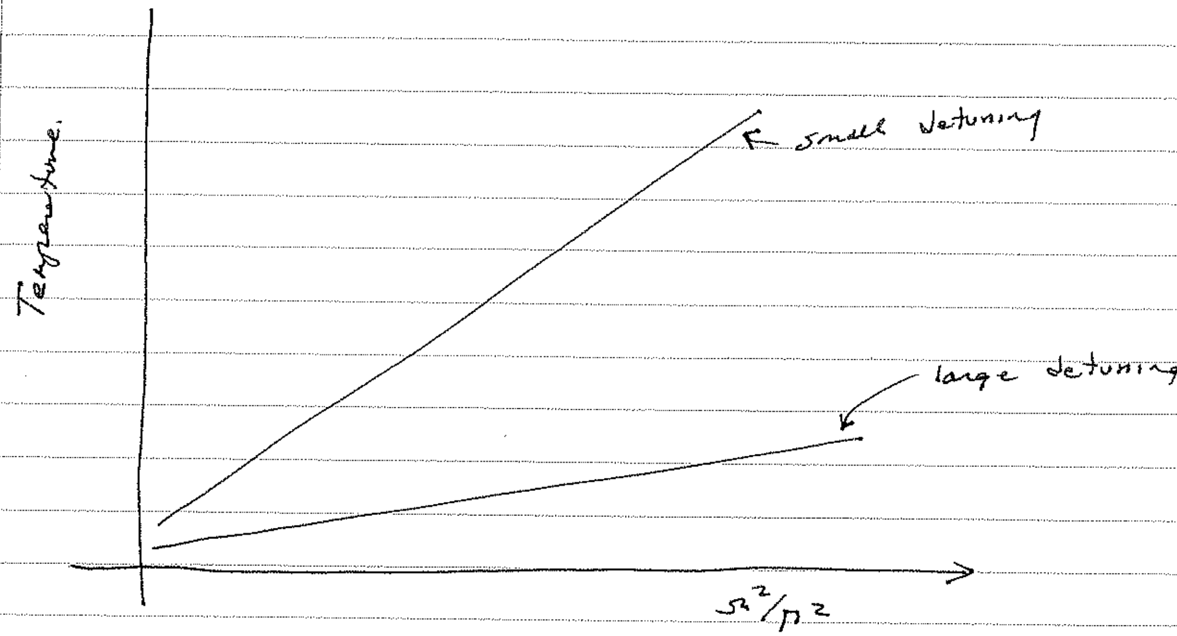
force fluctuates as atom pumps between potentials.

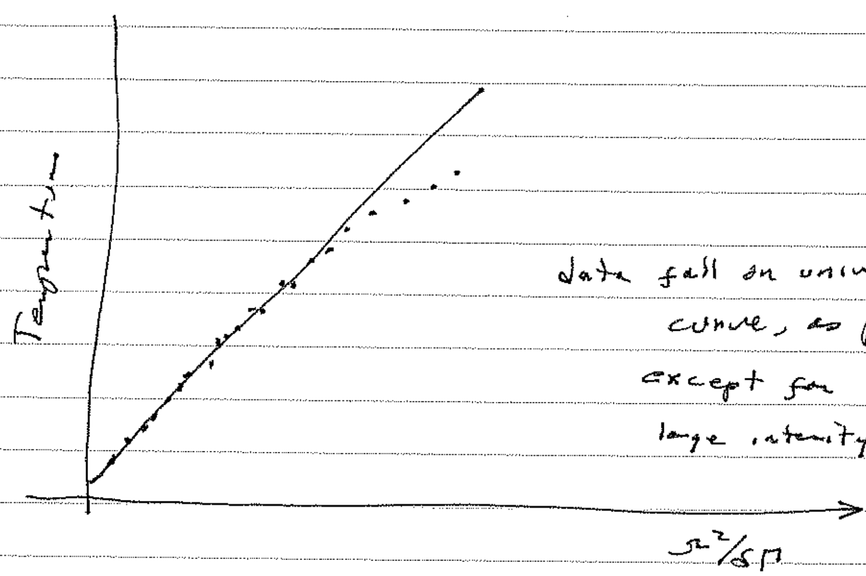
$$\mathcal{D}_p \sim \Big(\underbrace{\frac{\hbar\Omega^2}{\delta}}_{\sim U_0} \, k\Big)^2 \frac{1}{\Gamma \, \Omega^2/\delta^2} \sim \frac{\hbar^2 k^2 \Omega^2}{\Gamma}$$

k: derivative characteristic length

depends on intensity

$$k_B T = \mathcal{D}_p/\alpha \sim \frac{\hbar^2 k^2 \Omega^2}{\Gamma \hbar k^2 \delta/\Gamma} \sim \frac{\hbar \Omega^2}{\delta} \quad (\sim \text{light shift})$$





data fall on universal curve, as predicted except for small detunings, large intensity.

What about $\Omega^2 \to 0$? Does $T \to 0$?

No. (obviously)

the calculated $\mathcal{D}_p \sim \Omega^2$ is only the part due to fluctuations of the dipole force

there is another part, small for large Ω^2, due to photon recoil.

where $U_0 \sim E_{recoil}$, the atom loses less energy than it gains in an optical pumping cycle, so cooling stops.

$kT_{min} \sim E_{rec.}$

in practice $kT_m \simeq 4E_{rec.}$ ~~was~~ measured for Cs.

but $\frac{E_{rec}}{k} = 200\,nK$ for Cs

while $T_{Dopp}^{min} \cong 120\,\mu K$ for Cs.

so, "polarization-gradient" or "Sisyphus" cooling is

much more effective than Doppler cooling.

This enabled things like fountain clocks and Bose-Einstein Condensates.

short Topics :

Ramsey method

atomic clocks

fountain clocks

magnetic trapping