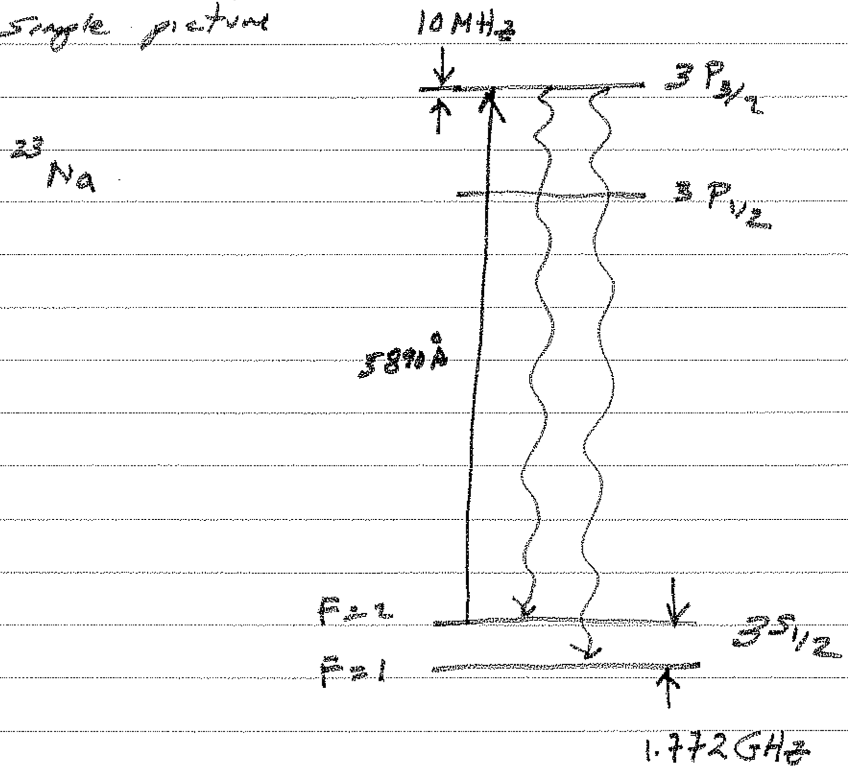
6 December 2005

Optical Pumping; sub-Doppler laser cooling

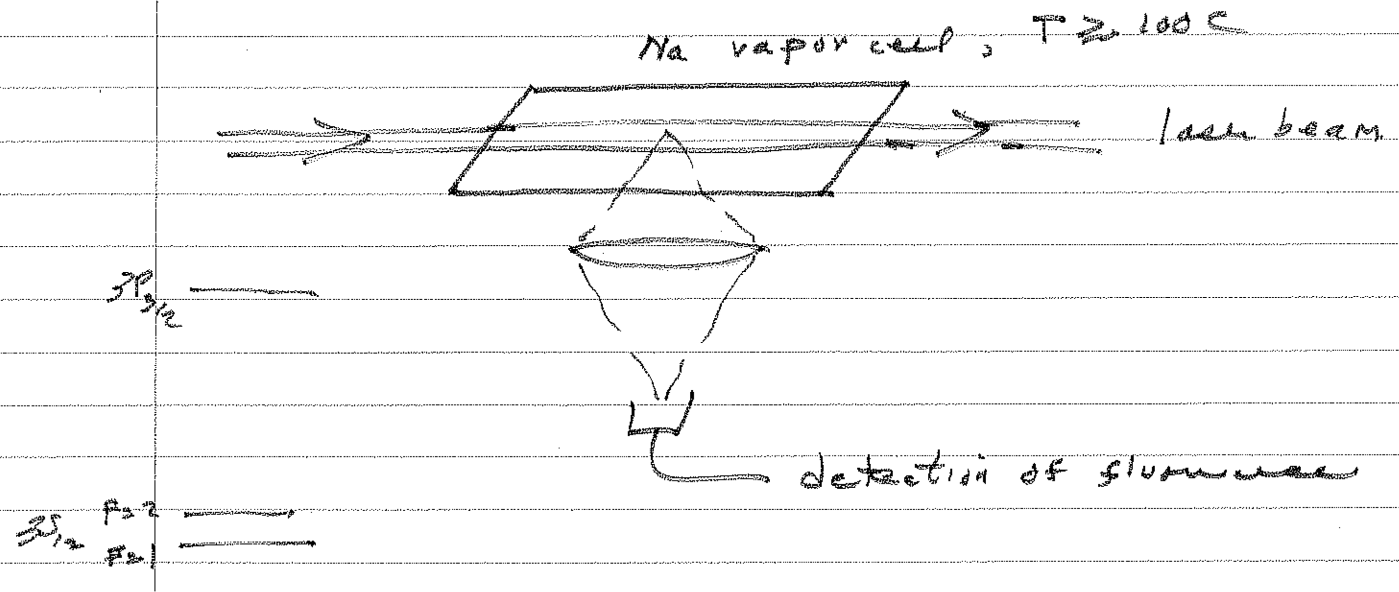
We saw that in laser cooling of alkali atoms optical pumping was a problem that interrupts the cooling process.

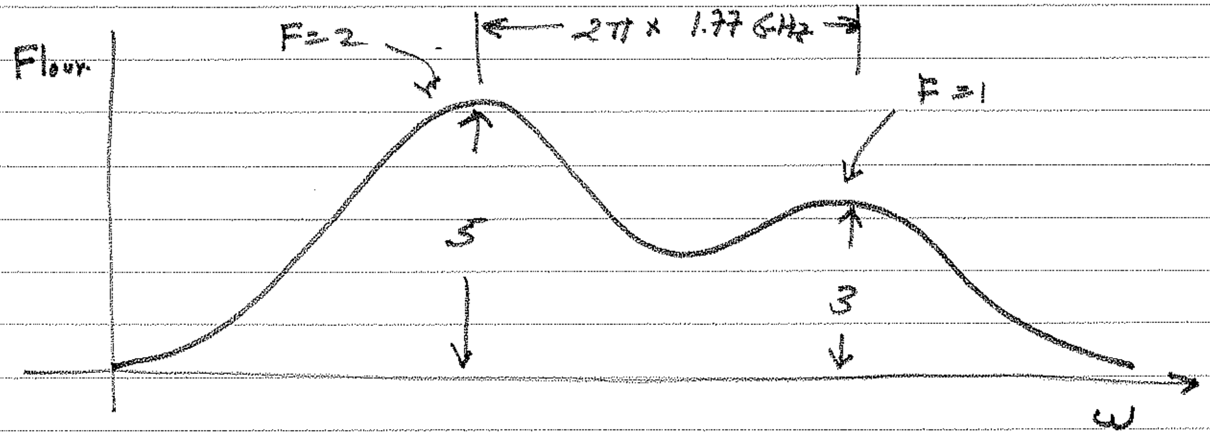
Simple picture



Excitation from $3S_{1/2}$, F=2 to $3P_{3/2}$ and subsequent decay to $3S_{1/2}$, F=1 leaves the population in F=1, off resonant by 1.77 GHz with a 0.01 GHz line width - a *very* low level of excitation — absorption essentially stops.

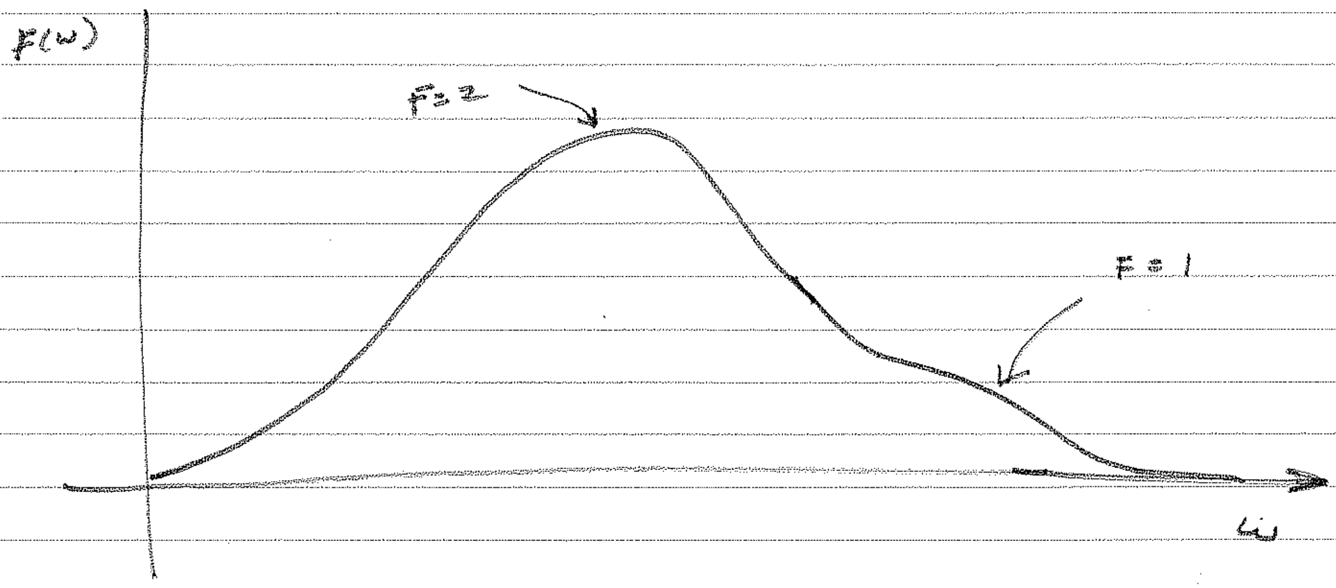
Another example of "bad" optical pumping effects.



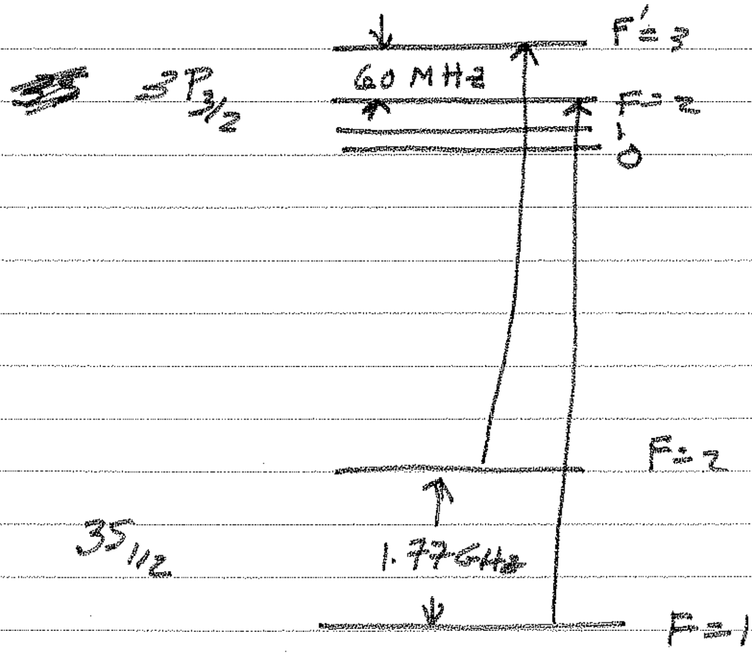


low intensity, small beam diameter, 2 Doppler-broadened peaks with intensity ratios according to the populations in grnd state. ($k_B T \gg \hbar \Delta\omega_{HFS}$ leads to equal population in all states (2F+1) states.

now increase the intensity to ~ saturation, use large beam diameter:



the F=1 peak is suppressed, because it optically pumps, while F=2 resists pumping. Why?



because $3S_{1/2}, F=2 \rightarrow 3P_{3/2}\ F'=3$ is closed

$\Delta F = \pm 1, 0$ selection rule makes $F'=3 \rightarrow F=2$ the only possible decay channel, and atoms can be re-excited, so $F=2$ atoms excited to $F'=3$ scatter many photons.

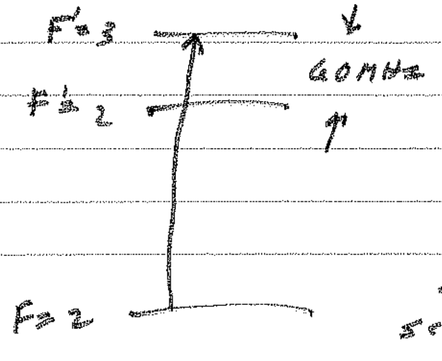
$3S_{1/2}\ F=1 \rightarrow 3P_{3/2}\ F'=2,1,0$ and

$F'=2,1$ can decay to $F=2$. Transition strength to $F'=0$ is small, and it is close to $F'=1$, so $F=1$ atoms are "lost" and do not scatter many photons.

This distorts the line shape - ratio of peaks. High intensity scatters many photons from an atom before it exits the large beam:

at high power, scatter a photon every $\gtrsim 32$ ns ($\tau = 16$ ns) and at 500 m/s, atoms traverse 1 mm in 2 μs.

But even the $F=2$ state eventually pumps, even when the atom velocity puts it on resonance for $F'=3$:



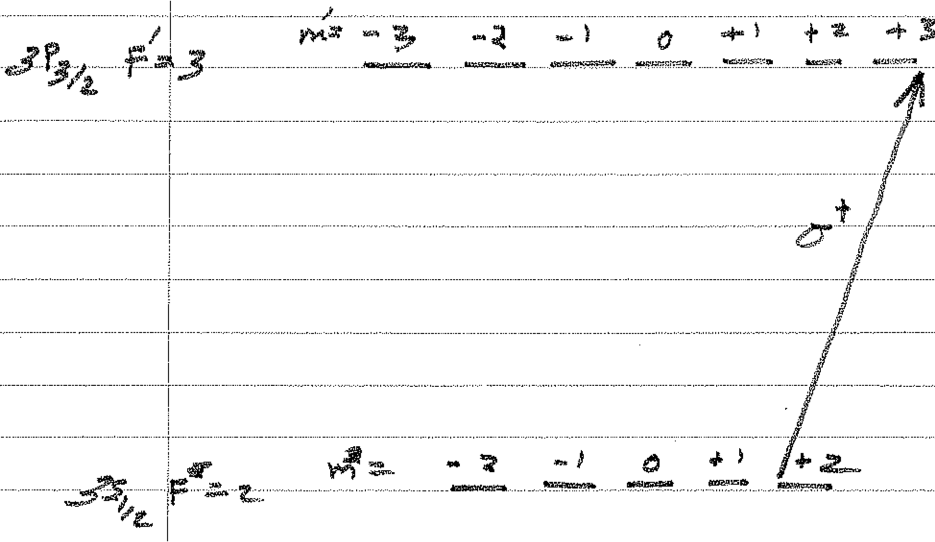
6 linewidths off resonance:

$$\chi = \frac{I/I_0}{1 + I/I_0 + (2\delta/\gamma)^2}$$

$(12)^2$

so, after a few hundred scatterings, this too will pump

But we have more tricks to manage optical pumping — angular momentum and ΔM selection rules.



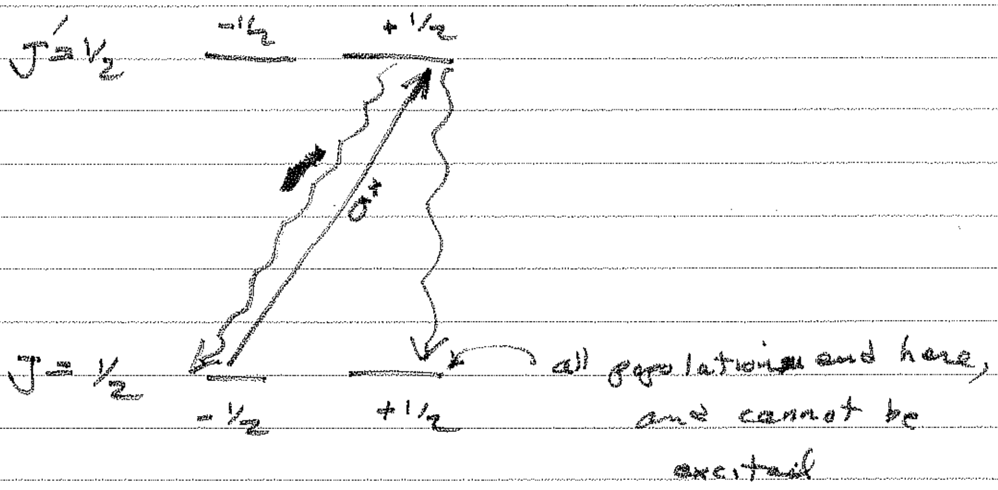
this transition is completely closed — $F'=3$, $m'=3$ will only decay to $F=2$ $m=2$.

better still, atoms in $F=2$, $m \neq +2$ will pump into $|F=2, m=+2\rangle$ after several absorptions — typically before they pump to $F=1$.

This is an important feature of Zeeman cooling. Optical pumping ensures that most atoms, regardless of initial state, will participate in the cooling.

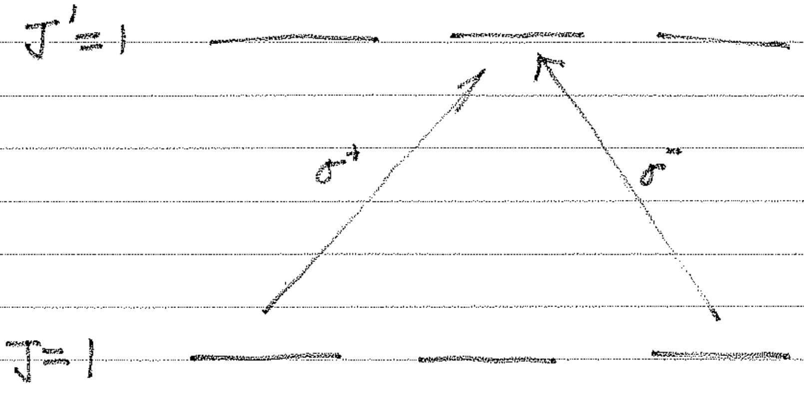
Optical pumping is often used to prepare an atomic sample in a given internal state.

sometimes a transition pumps dark:



Often, optical pumping can be understood in terms of population rate equations — only the diagonal elements of the density matrix are needed.

But not always:

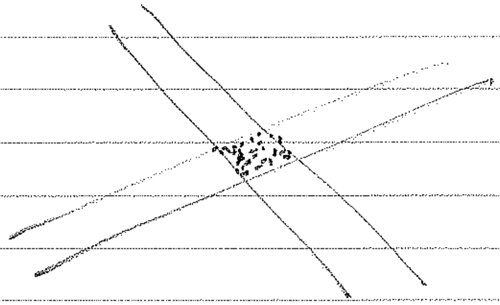


this system pumps dark, but off-diagonal terms are important.

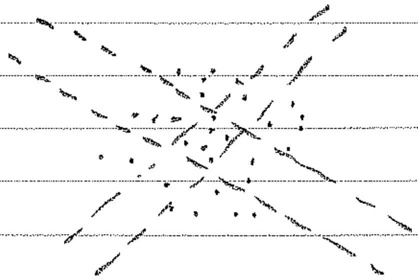
This was discovered in ~1976 by Ennio Arimondo et al. He will guest lecture on the subject of coherent population trapping.

Experimental results of laser cooling in optical molasses.

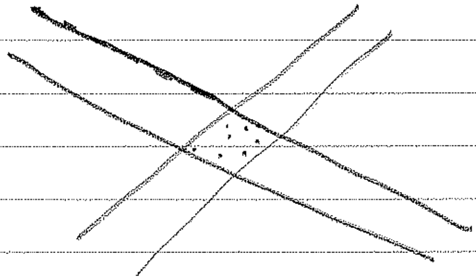
How to measure the temperature?



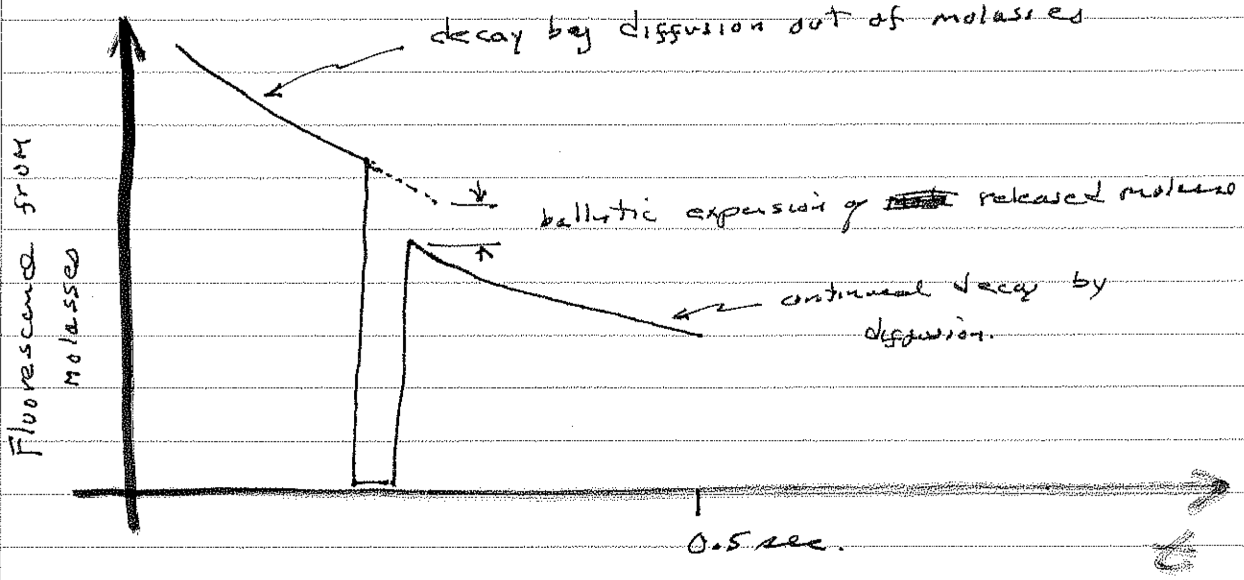
optical molasses
atoms held viscously
in equilibrium with radiation cooling and heating.



released cloud expands with thermal velocities



re-applying laser beams "re-capture" those atoms still in intersection region.



decay of molasses is approx. exponential.

interpretation of release + re-capture is difficult because of shape of laser beams, intersection region, gravity, etc.

recall: $k_B T = \frac{\hbar\Gamma}{4} \frac{1+(2\delta/\Gamma)^2}{(2\delta/\Gamma)}$

minimizes at $(2\delta/\Gamma)=1$ for $k_B T_{min} = \frac{\hbar\Gamma}{2}$

for Na. $\Gamma/2\pi = 10\,MHz$.

$T_{min} = 240\,\mu K$.

measurement above at Bell Labs 1985 gave

$T = 240^{+200}_{-60}\,\mu K$. confirmed later at NIST - Gaithersburg

similar results at JILA - U. of CO for Cs gave $kT = \hbar\Gamma/2$.

Problems with optical molasses:

- why is $T = T_{min}$ when T_{min} is the $I/I_0 \to 0$ and $\delta = \Gamma/2$ limit - and these were not carefully maintained.

- gravity or an imbalance in laser beams would cause a drift velocity

$$v_{drift} = \underset{\uparrow \ \text{unbalanced force}}{F}/\alpha \leftarrow \text{friction coefficient}$$

for optimum damping find approximately

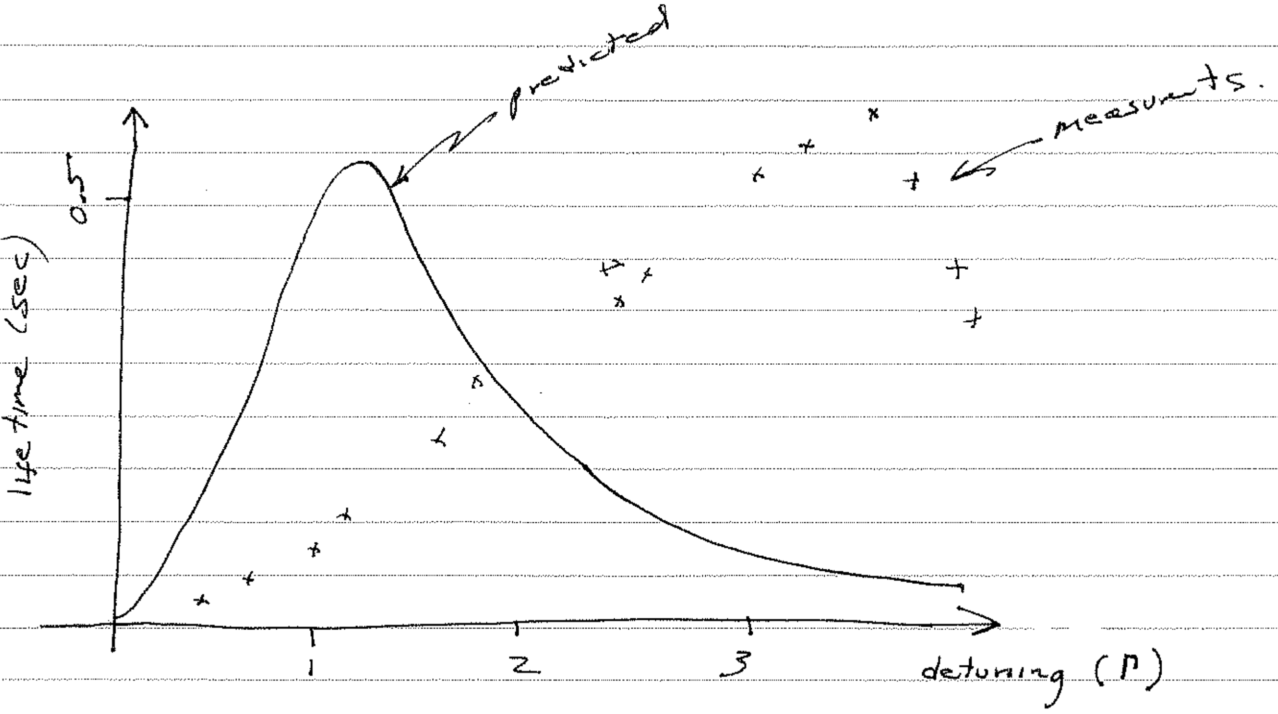
$v_{drift} = \epsilon\Gamma/2k$ for Na $\Gamma/2k = 3\,m/s$

so even a 1% imbalance (hard to be that good) would give 3 cm/s drift - but 1 cm molasses lasts ~ 1 sec (exponential time constant)

Measurements of drift with deliberate imbalance ~~to~~ gave much less effect than expected.

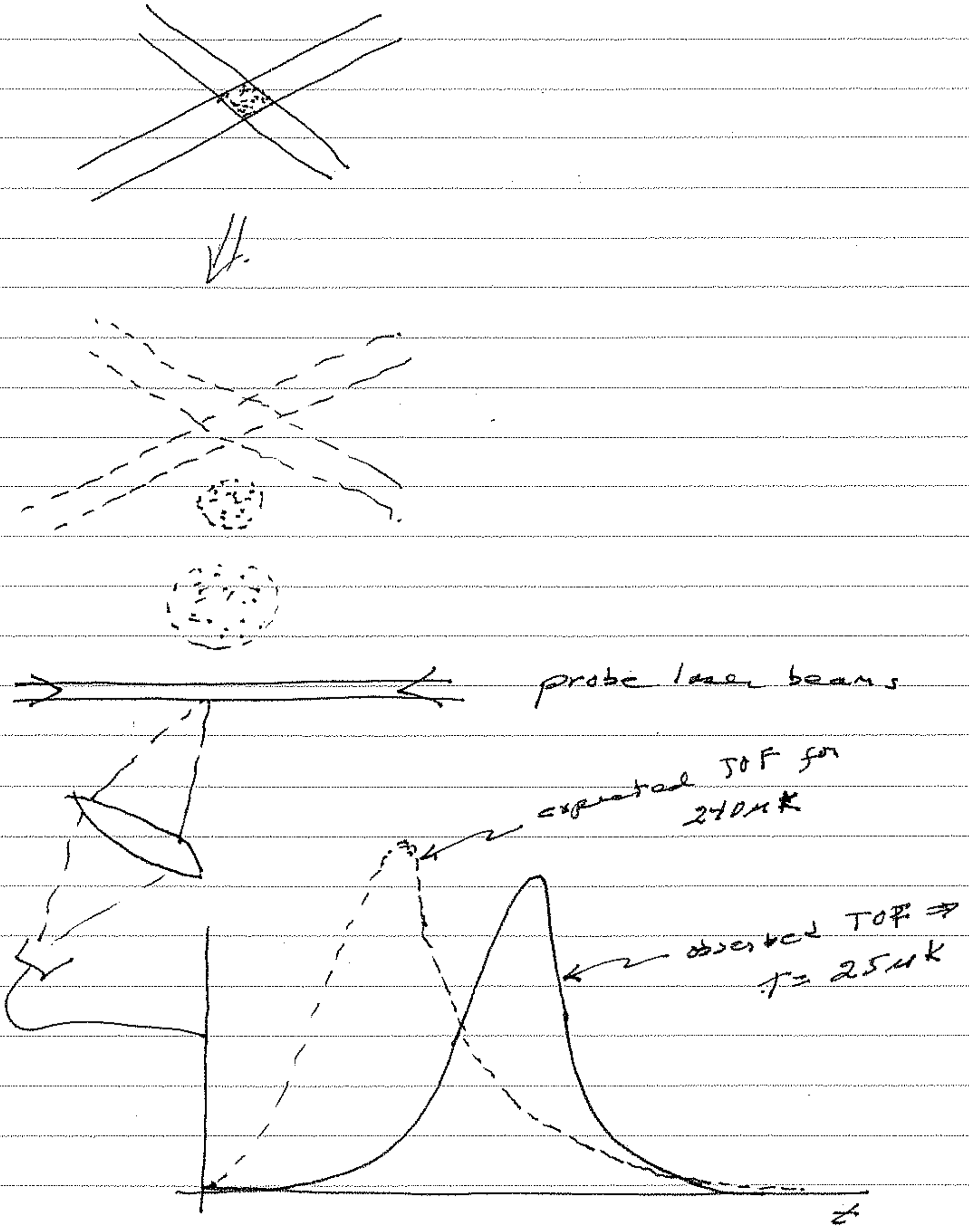
If we believe $v_{drift} = F/\alpha$

then α appears to be larger than allowed by Doppler cooling.



Lifetime is optimal at much larger detuning than predicted by molasses in Doppler cooling.

A different temperature measurement:



the temperature for Na was as much as 10 times lower than the lowest predicted by Doppler cooling theory