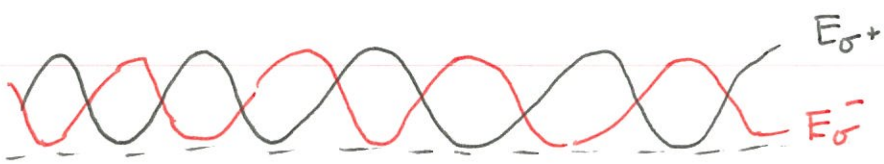
Lec. 16
10/19/2017

Sisyphus cooling

→ simplified picture in 1D, lin ⊥ lin configuration

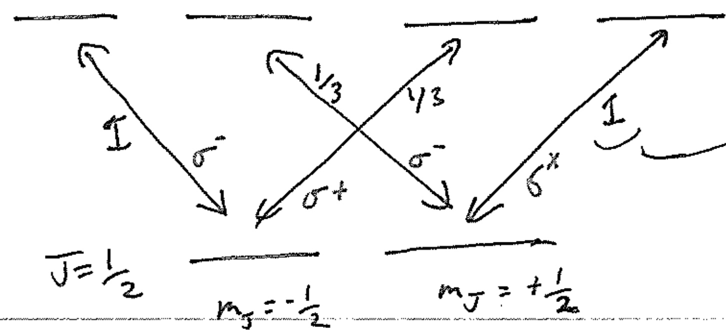
$J = \frac{1}{2} \leftrightarrow J = \frac{3}{2}$ transition

$\vec{E}_R = E_y \cos(kz - \omega t)\,\hat{y}$ $\qquad$ $\vec{E}_L = E_x \cos(-kz - \omega t)\,\hat{x}$



$\vec{E}_{TOT}$ can be written in term of $\hat{x}, \hat{y}$ linear polarizations, which have uniform amplitude (along z), or in terms of σ^+ and σ^- polarizations, which have sinusoidally varying and complementary amplitudes (along z).

$J=\frac{1}{2} \leftrightarrow J=\frac{3}{2}$ transition



ang. momentum part of $|\langle g|\hat{\epsilon}\cdot\vec{r}|e\rangle|^2$

Because of the form of the transition strengths, the states $m_J = \pm 1/2$ are more strongly coupled to $\sigma^{\pm}$ light

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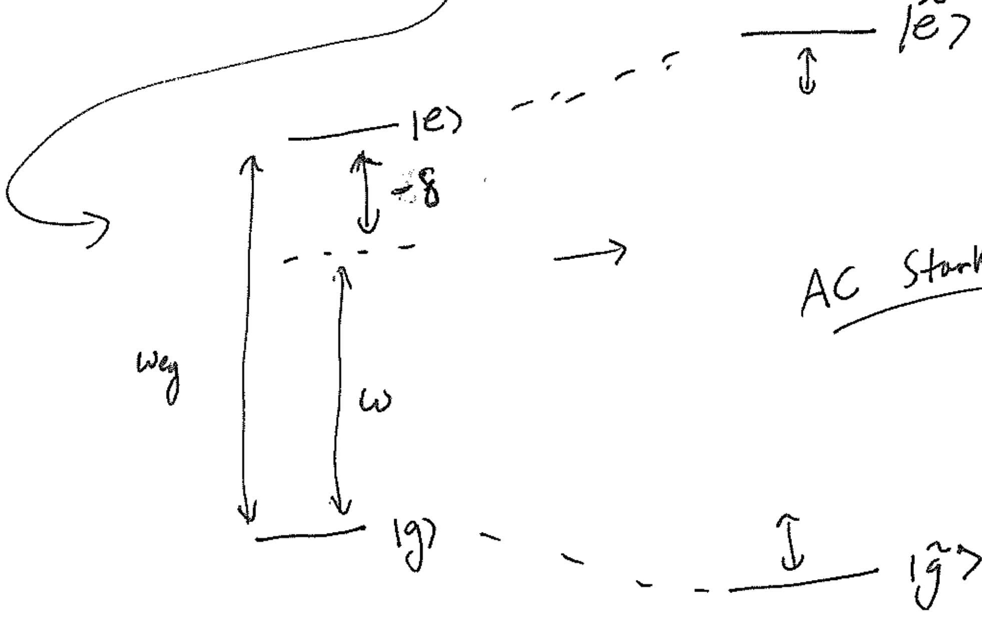
When $\delta < 0$ $(\omega < \omega_{eg})$, one gets cooling due to combination of light shifts + optical pumping.



AC Stark effect

shifted in energy by $-\frac{\Omega^2}{2\delta}$

shifted in energy by $\frac{\Omega^2}{2\delta}$

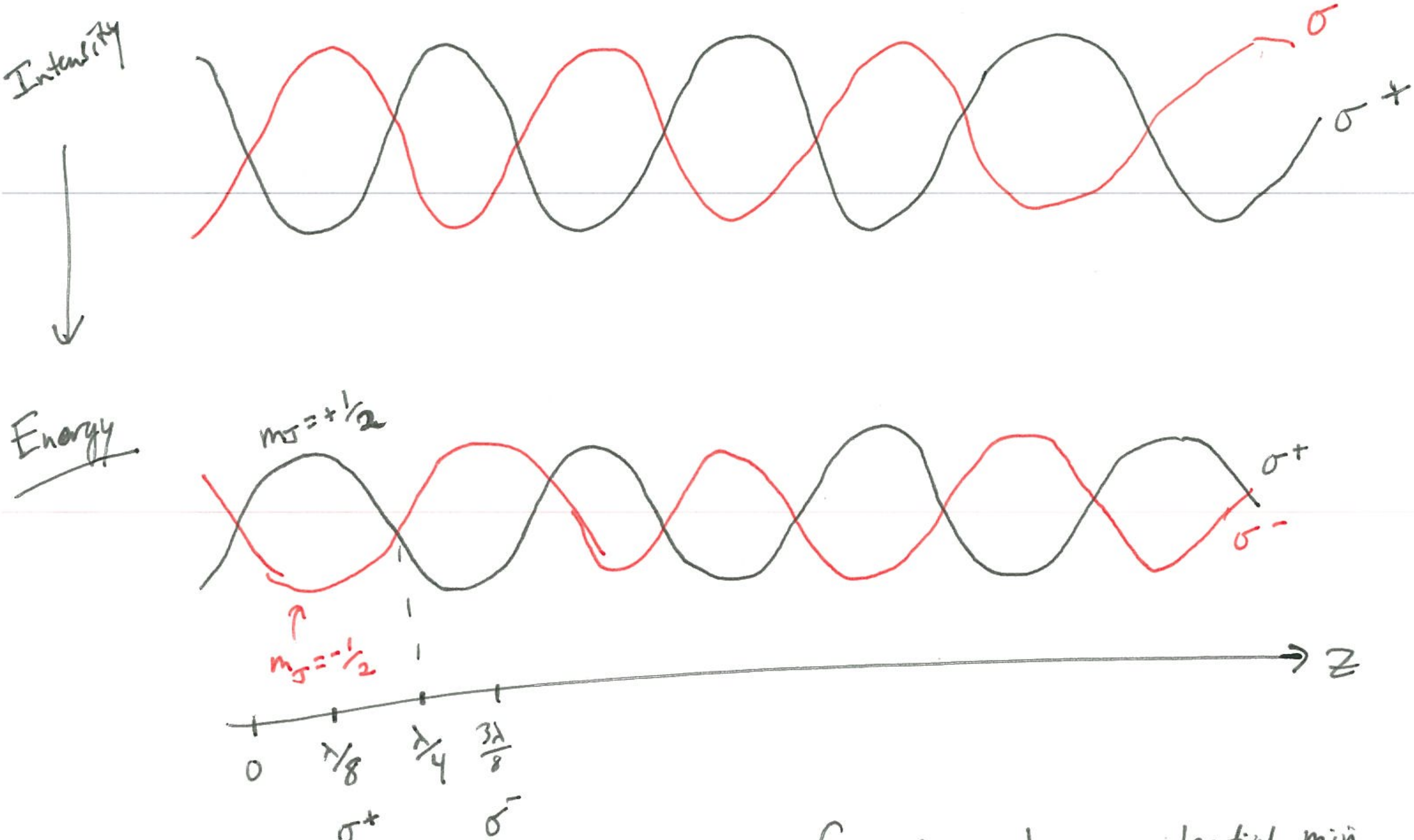
assume large detuning $|\delta| \gg \Omega$

(lower if $\delta < 0$) $\omega < \omega_{eg}$

Intensity ($\propto |\Omega|^2$) is proportional to light shift or energy of the m_J states

$\Delta E_g \propto -I$

for $\delta < 0$



for $m_J = -\frac{1}{2}$, potential min when σ^- is strongest.

potential max when σ^+ is strongest (most intense).

optical pumping to $m_J = +\frac{1}{2}$ is strongest when σ^+ is maximal (i.e. @ top of hill).

So, atoms go up hill (lose energy) and then get optically pumped to bottom of the hill

[reverse is true for $m_J = +\frac{1}{2}$]

So, energy is lost as particles go up the hill.

For $|\delta| \gg \Omega$, $\Delta E \sim \frac{\hbar |\Omega|^2}{2\delta} \propto \frac{I}{\delta}$

$$\sim \frac{\hbar \Gamma^2 s}{4\delta} \quad \text{w/ } s = I/I_{sat}$$

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called "Sisyphus cooling," associated w/ endless rolling up the hill. Entropy is lost (removed) to the light field via spontaneous emission (spont. Raman scattering)

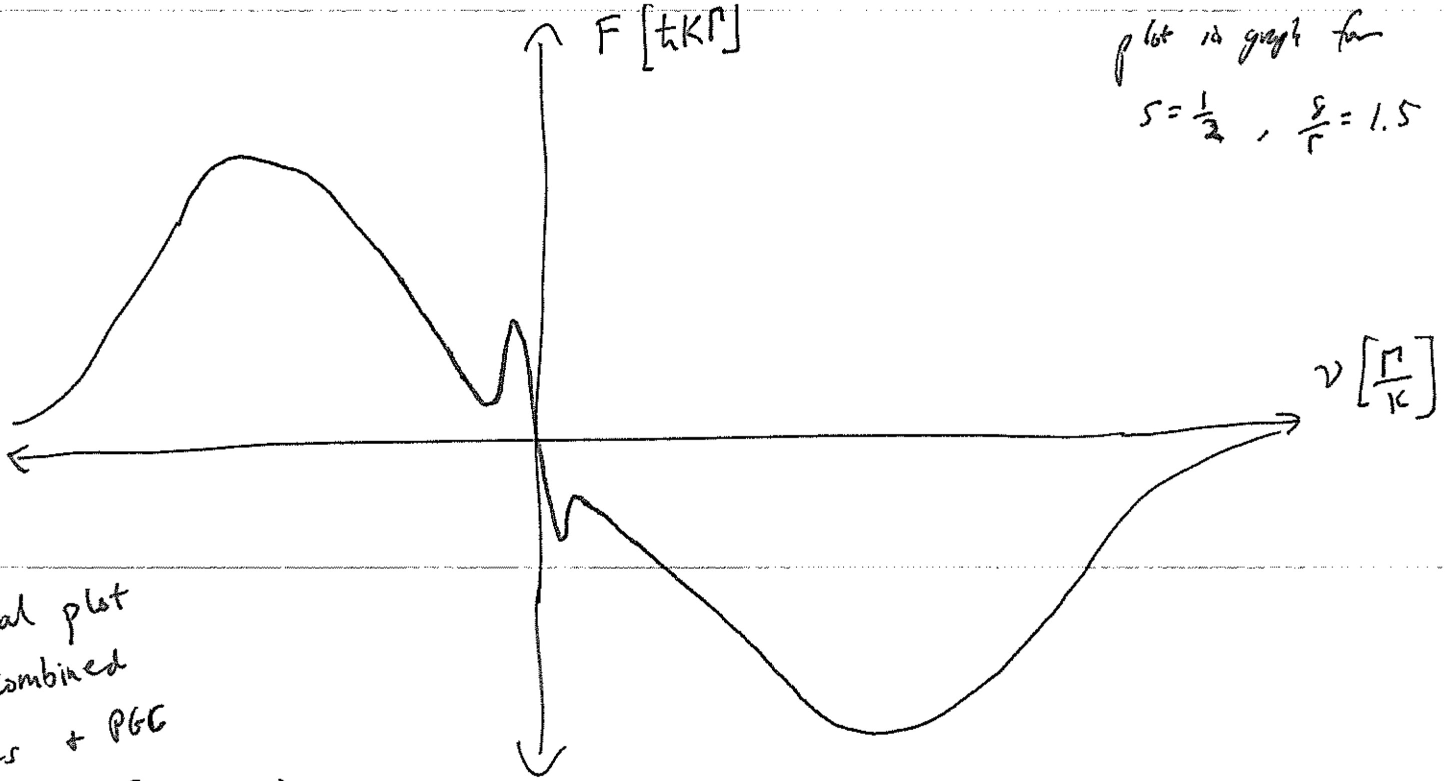
The PGC force is dominant @ small velocities,
pol. grad. cooling

$$v < v_c^{PGC} \sim \frac{R}{K}$$

R ← optical pumping rate

K ← spatial frequency relating to polarization change ($2K_\lambda$)

The cooling coefficient associated w/ PGC can be much larger than for molasses, and so it can achieve much lower temperatures (when considering the limitation of recoils due to spontaneous decay) plot is graph for $s = \frac{1}{2}$, $\frac{\delta}{\Gamma} = 1.5$



general plot of combined molasses + PGC forces vs. velocity (Dopplershift)

larger $|B|$, lower equilibrium temperature

$\Rightarrow$ close to recoil limit for some alkalis

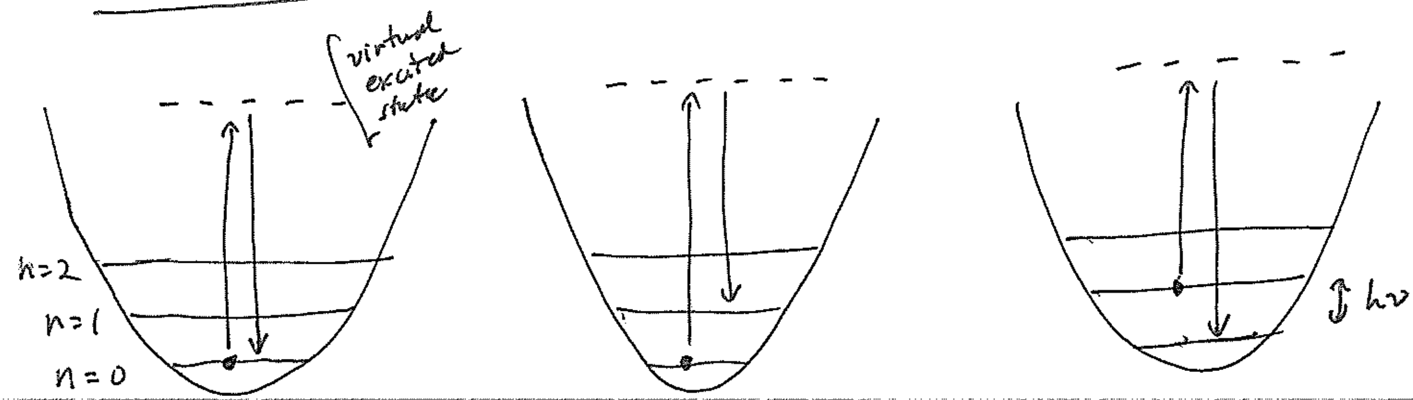
$\sim 10 \times T_{rec}$ for Cs where $T_{rec} \sim 200\,nK$,

$T_{PGC} \sim$ few μK (similar for ^{87}Rb)

$$\left[T_{rec} = \frac{1}{k_B} \frac{\hbar^2 k^2}{2m} \right]$$

~ harmonic oscillator, relevant to molecules, vibrations in solids, etc.

Stokes + anti-Stokes scattering



Rayleigh scattering

$\Delta n = 0$

Stokes scattering

$\Delta n = +1$

$\Delta E_{light} = -h\nu$

anti-Stokes scattering

$\Delta n = -1$

$\Delta E_{light} = +h\nu$

The rates of these spontaneous scattering processes depend on distribution of n_ν populations

(if $P_\nu \propto e^{-E_\nu/kT}$, then depend on <u>temperature</u>).

in thermal equil., $P_{n-1} > P_n$,

such that Stokes peak is stronger than anti-Stokes

[scattering rates can be used for thermometry!]

Some considerations for Raman sideband cooling

initial KE $\sim k_B T$ compared to trap depth U_0.

only works if potential looks harmonic for states that are occupied.

$\Delta E(n+1 \to n) \simeq \Delta E(n \to n-1)$

$\cdots$

Lamb-Dicke regime

$\eta^2 (2n+1) \ll 1$ w/ n the quantized motional state index

w/ $\eta_x \doteq \left(\frac{2\pi}{\lambda}\right) X_0$

Also $\vec{K}_{Raman}$ needs some projection onto the direction being cooled $\Rightarrow$ to couple $|n\rangle_x, |n-1\rangle_x$, need $K_x \neq 0$

approximate the potential

$U_0 \cos^2\left(\frac{2\pi x}{\lambda}\right)$ 

as $\frac{1}{2} m \omega_{HO}^2 X^2$, near minimum

↳ g.s. harmonic oscillator length $X_0 = \sqrt{\frac{\hbar}{m\omega_{HO}}}$

$X_0 \approx \frac{\lambda}{2\pi s^{1/4}}$

w/ $s = \frac{U_0}{E_R}$

$E_R = \hbar^2 k^2 / 2m$