Sisyphus cooling

→ simplified picture in 1D, lin-1 lin configuration

\[ \mathbf{E}_x = E_x \cos (kz - \omega t) \hat{x} \]

\[ \mathbf{E}_y = E_y \cos (kz - \omega t) \hat{y} \]

\[ \mathbf{E}_z = E_z \cos (kz - \omega t) \hat{z} \]

\[ J = \frac{1}{2} \leftrightarrow J = \frac{3}{2} \] transition

\[ \mathbf{E}_{0^+} \] and \[ \mathbf{E}_{0^-} \]

\[ \mathbf{E}_{\text{total}} \]

can be written in terms of \( \hat{x}, \hat{y} \) linear polarizations, which have uniform amplitude (along \( z \)), or in terms of \( \sigma^+ \) and \( \sigma^- \) polarizations, which have sinusoidally varying and complementary amplitudes (along \( z \)).
Because of the form of the transition strengths, the states $m_J = \pm \frac{1}{2}$ are more strongly coupled to $\sigma^\pm$ light when $\delta < 0$ (\( \omega < \omega_{eg} \)), one gets cooling due to combination of light shifts + optical pumping.

Assume large detuning $|\delta| \gg \omega$
Intensity ($\propto |\psi|^2$) is proportional to light shift or energy of the $m_\gamma$ states.

$$\Delta E_g \propto -I$$

for $\gamma < 0$

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

[reverse is true for $m_\gamma = +\frac{1}{2}$]
So, energy is lost as particles go up the hill.

For \( 187 > \sigma \), \( \Delta E \sim \frac{k \sigma^2}{28} \propto \frac{I}{s} \)

\( \sim \frac{k \sigma^2 s}{4} \quad \text{with} \quad s = \frac{I}{I_{sat}} \)

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

pol. grad. cooling

The PGC force is dominant @ small velocities,

\( \nu < \frac{\nu_{pol}}{R} \)

\( \frac{R}{K} \) spatial frequency relating to polarization change (2K)

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)
larger $|\beta|$, lower equilibrium temperature

close to recoil limit for some alkalis

$\sim 10 \times \text{Tree for Cs where Tree} \approx 200 \text{mk},$

$T_{Ge} \sim \text{few mk}$ (similar for $^{87}\text{Rb}$)

$T_{\text{rec}} = \frac{1}{2m} \frac{k^2}{k_B^2}$
Stokes and anti-Stokes scattering

virtual excited state

stokes scattering

$\Delta n = +1$

$\Delta E_{\text{light}} = -\hbar \nu$

anti-Stokes scattering

$\Delta n = -1$

$\Delta E_{\text{light}} = +\hbar \nu$

The rates of these scattering processes depend on distribution of $n$, population

$P_n \propto e^{-\frac{n}{kT}}$ (if $P_n \propto e^{-\frac{n}{kT}}$, then depends on temperature).

in thermal equilibrium $P_{n-1} > P_n$

such that Stokes peak is stronger than anti-Stokes

[scattering rates can be used for thermometry!
Some considerations for Raman sideband cooling

initial $KE \sim kBT$ compared to trap depth $U_0$.

only works if potential looks harmonic

for states that are occupied.

\[ \Delta E (n+1 \rightarrow n) \approx \Delta E (n \rightarrow n-1) \]

\[ \zeta_n^2 (2n+1) \ll 1 \]

\[ \xi_x = \left( \frac{2\pi}{\zeta} \right) x_0 \]

Lamb-Dole regime

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

Also Raman needs some projection onto the direction being cooled to couple $|m_x, m-1|, |m_x, m|$.

$K_x \neq 0$

approximate the potential

\[ \frac{1}{2} m \omega_0^2 x^2 \]

near minimum

4 d.g.s. harmonic oscillator length

\[ x_0 = \sqrt{\frac{\hbar}{m \omega_0}} \]

$X_0 = \frac{\lambda}{2\pi S^{1/4}}$

$S = \frac{U_0}{E_R}$

$E_R = \frac{kT^2}{2m}$