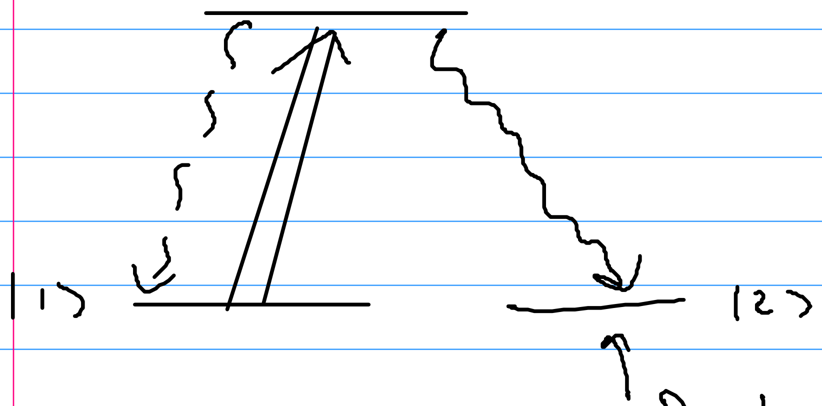
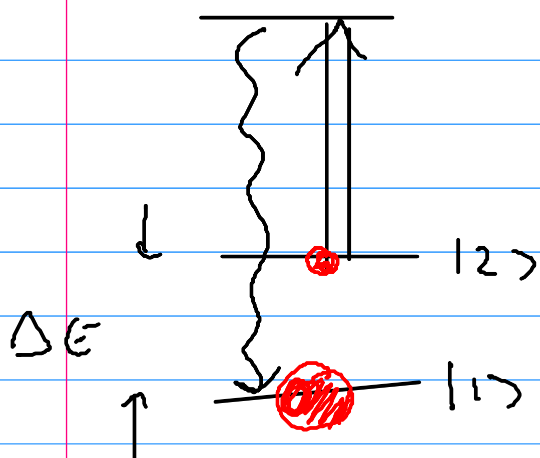
Optical cooling

Sub-Doppler, Sub-Recoil } Temp.

Cooling by optical pumping





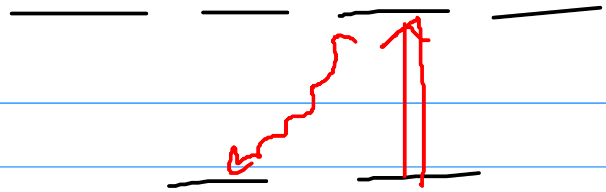
$$\frac{n_2}{n_1} = e^{-\beta \Delta E}$$

$n_2 \to 0$ $\qquad$ $T \to 0$

Sub-Doppler cooling

New effects in multilevel atoms

"Polarization gradient cooling" is the most famous example



$J = 3/2$

$J = 1/2$

resonances between ground states

width $\Gamma' = \dfrac{1}{\tau_p} \sim \underbrace{\dfrac{\Omega^2}{\delta^2}\,\Gamma}_{\text{optical pumping rate}} \ll \Gamma$

$\Rightarrow$ long relaxation time

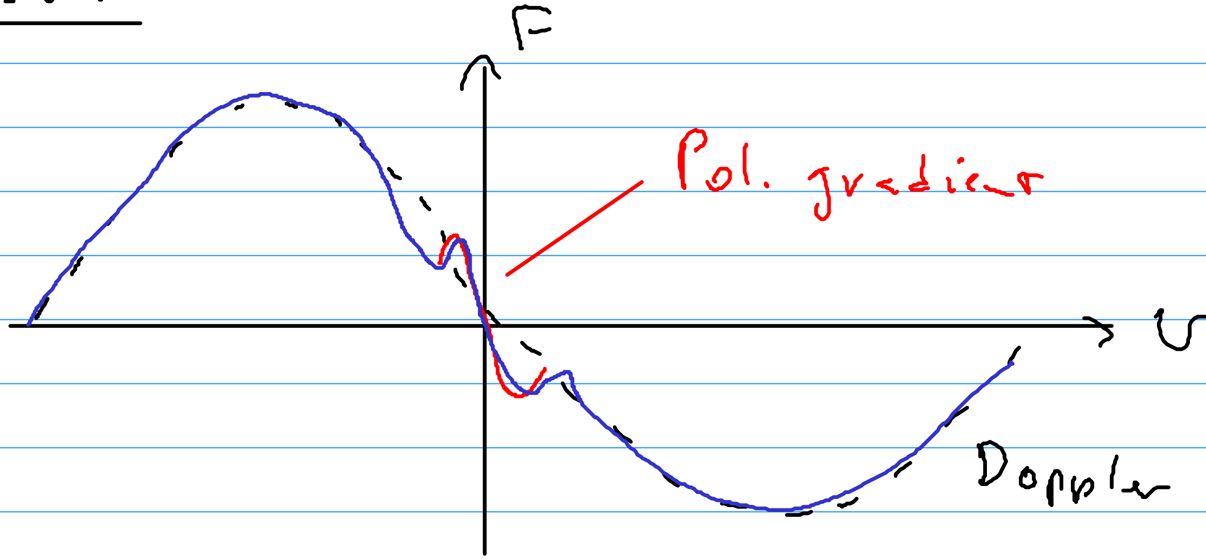
$\Rightarrow$ possibility of large time lags

$\Rightarrow$ cooling

often $k_B T_{final} \propto \hbar \Gamma'$ eg. Doppler cooling

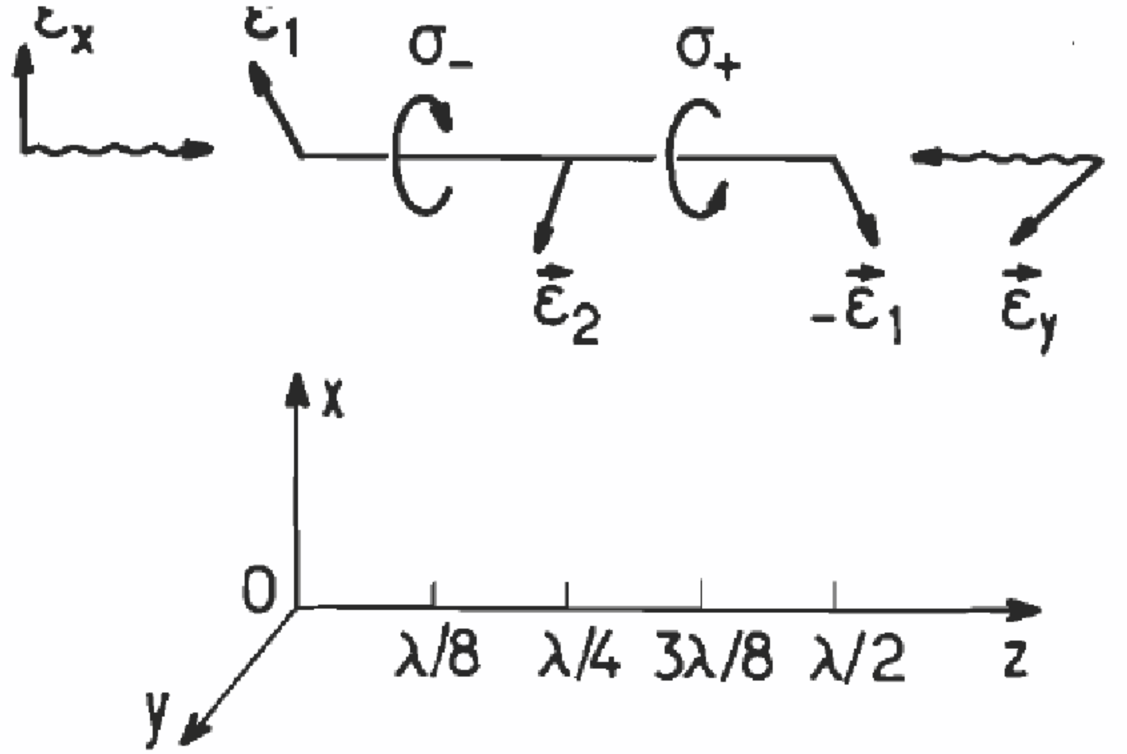
(but here $\Gamma' \; \dfrac{\Gamma}{\delta}$)

Result



Laser cooling below the Doppler limit by polarization gradients: simple theoretical models

J. Dalibard and C. Cohen-Tannoudji



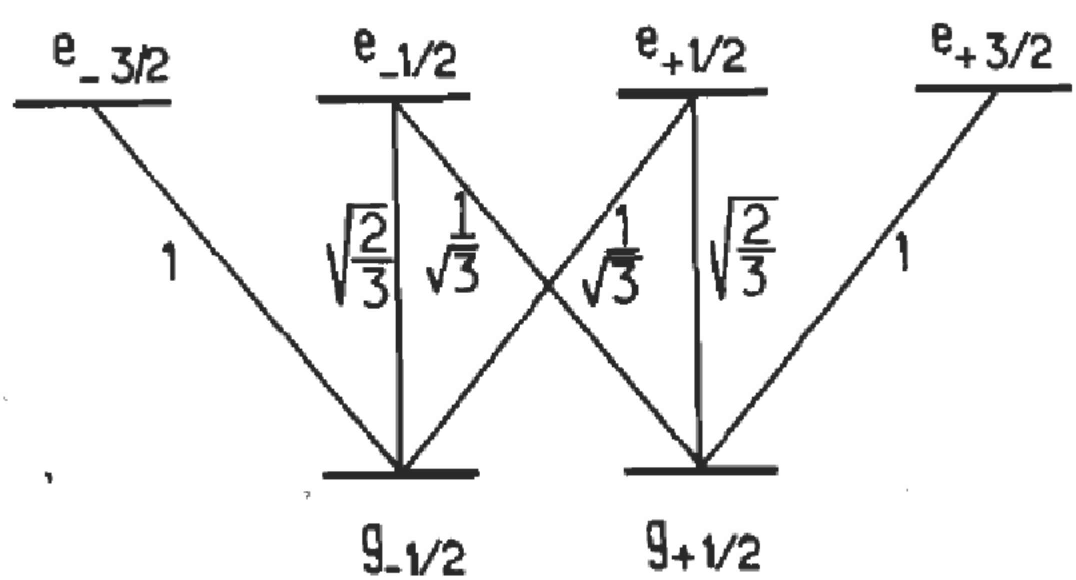


Fig. 2. Atomic level scheme and Clebsh–Gordan coefficients for a $J_g = 1/2 \leftrightarrow J_e = 3/2$ transition.

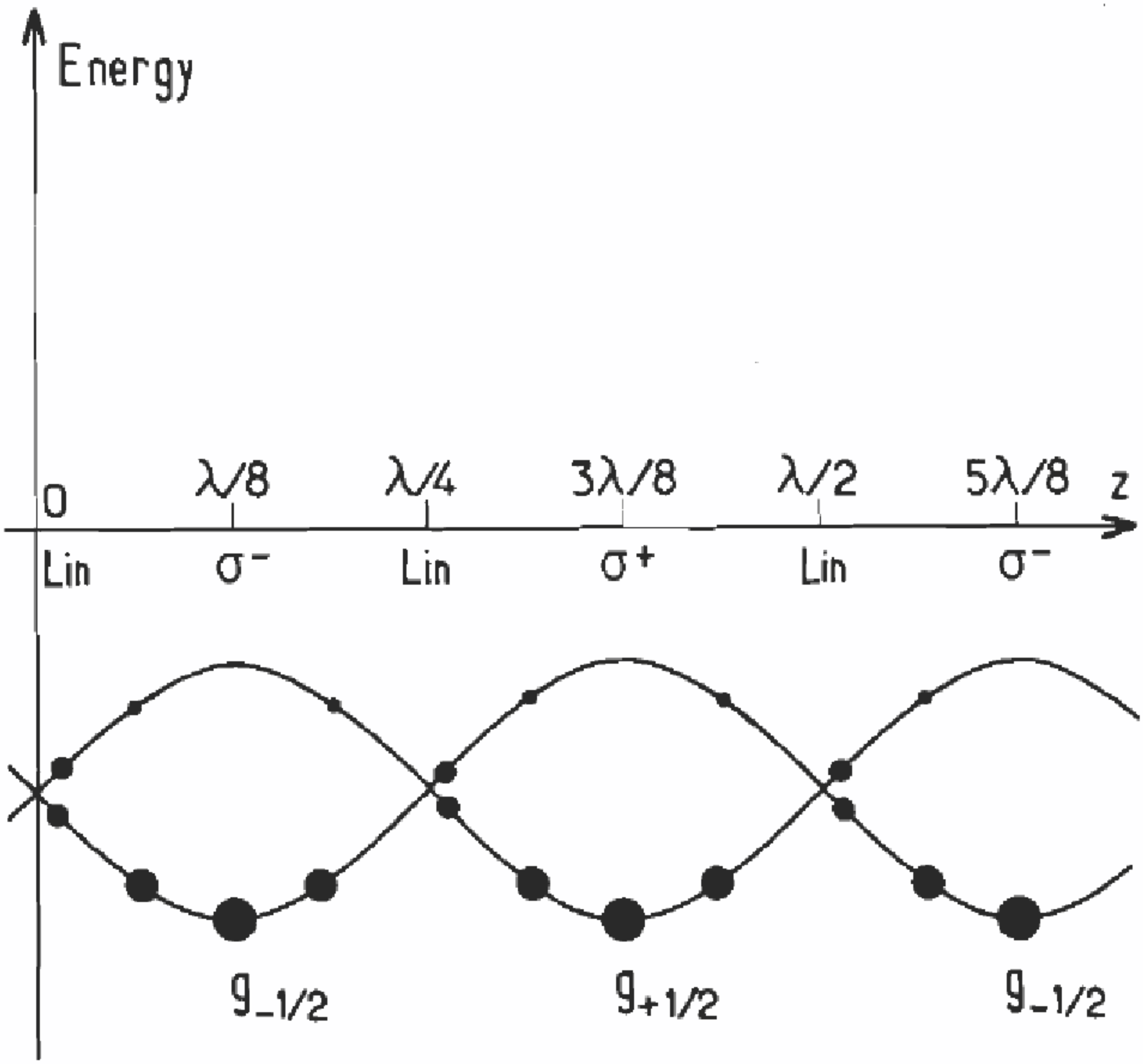


Fig. 3. Light-shifted energies and steady-state populations (represented by filled circles) for a $J_g = 1/2$ ground state in the lin $\perp$ lin configuration and for negative detuning. The lowest sublevel, having the largest negative light shift, is also the most populated one.

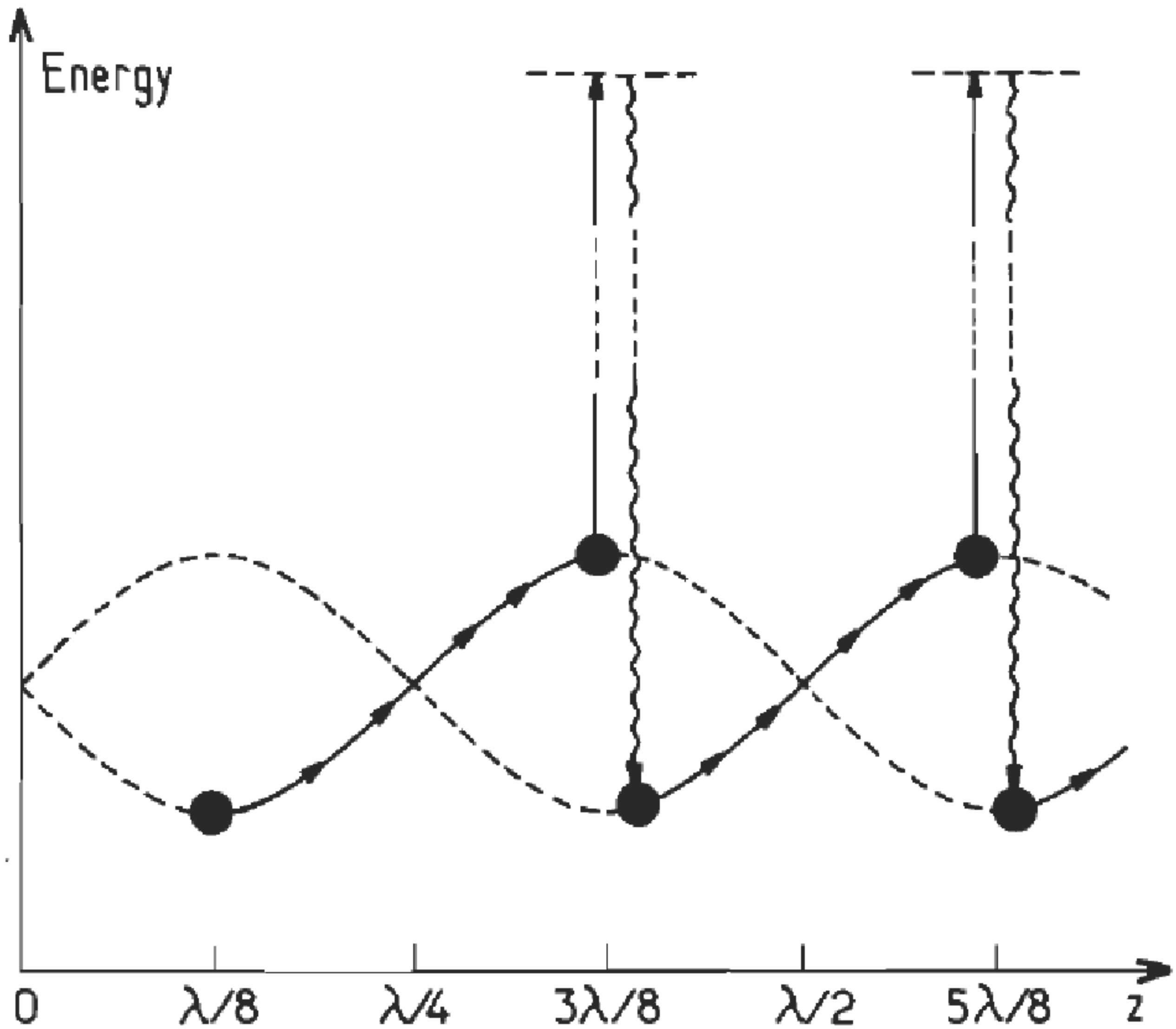


Fig. 4. Atomic Sisyphus effect in the lin $\perp$ lin configuration. Because of the time lag τ_p due to optical pumping, the atom sees on the average more uphill parts than downhill ones. The velocity of the atom represented here is such that $v\tau_p \sim \lambda$, in which case the atom travels overs λ in a relaxation time τ_p. The cooling force is then close to its maximal value.

Sub-recoil Cooling

Proof of impossibility

initial energy $\quad \frac{1}{2} m \vec{v}^{\,2}$

after abs. $\quad \frac{1}{2}\left(m\vec{v} + \hbar \vec{k}_L\right)^2$

after em. $\quad \frac{1}{2}\left(m\vec{v} + \hbar \vec{k}_L - \hbar \vec{k}_e\right)^2$

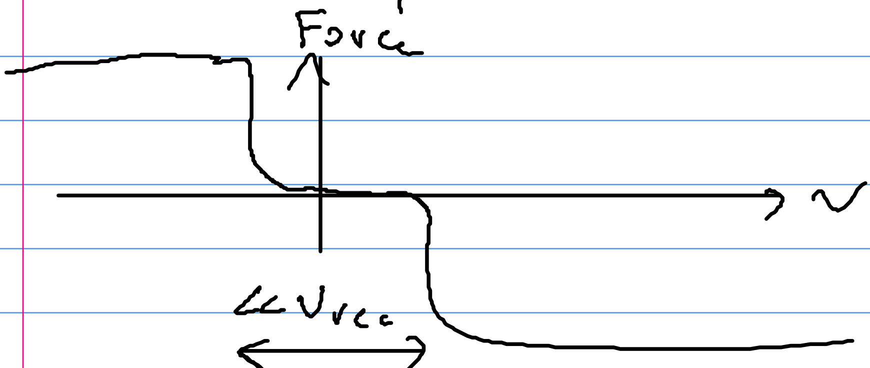
$$\Delta E = 2E_{rec} + \hbar\left(\vec{k}_L - \underset{\substack{\uparrow \\ \text{random}}}{\vec{k}_e}\right)\cdot\vec{v}$$

$$\overline{\Delta E} = \underset{}{\overset{\frac{k_L^2}{m}}{2E_{rec}}} + \hbar \vec{k}_L \cdot \vec{v}$$

cooling requires $\vec{k}_L$ antiparallel to $\vec{v}$

$\Rightarrow \quad \overline{\Delta E} < 0$ requires $v > v_{rec} = \frac{\hbar k_L}{m}$

BUT: the last scattered photon may not be random



Velocity-space Optical pumping

Practical implementations
- Raman Cooling
- VSCPT