11. Cooling and trapping of Atoms

11.1. Principle of laser cooling

- Radiation pressure

  - absorption: momentum transfer from photon to atom in the direction of the laser beam
  - spont. emission: momentum transfer into random direction

$\hookrightarrow$ absorption: $\langle \vec{p} \rangle = \hbar \vec{k}_L$, $\vec{k}_L$: mom. of photon from laser beam

emission : $\langle \vec{p} \rangle = 0$

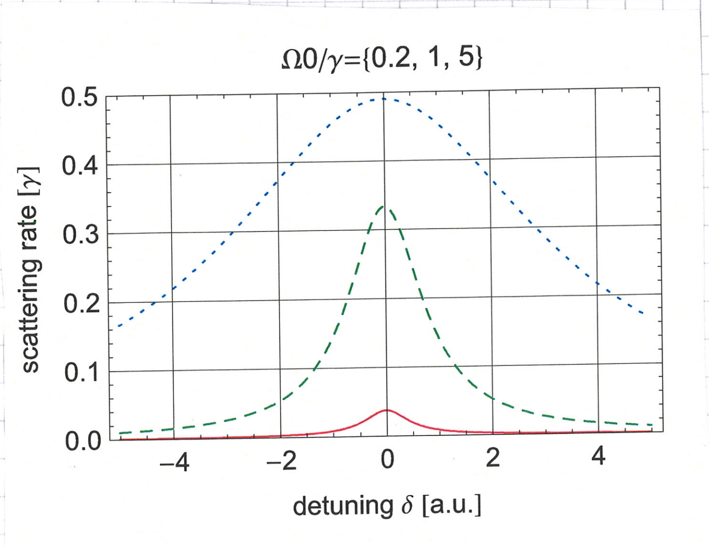
- force on the atom:

$$\vec{F} = \underbrace{\text{photon momentum}}_{\hbar \vec{k}_L} \times \underbrace{\text{scattering rate}}_{\gamma \cdot \rho_{22}}$$

chapt. 1.3

(13.1) $$= \hbar \vec{k}_L \cdot \frac{\gamma}{2} \frac{S_0}{1 + S_0 + \frac{4\delta^2}{\gamma^2}} \quad , \quad S_0 = \frac{2 \cdot \Omega_0^2}{\gamma^2}$$

$$= F(\delta)$$



- acceleration:

$a = F/m$

$\hookrightarrow a_{max} = \frac{\hbar k_L}{m} \cdot \frac{\gamma}{2}$

$\approx 10^6 \frac{m}{s^2} \sim 10^5 g$

for Na atoms (sodium)

$\hookrightarrow$ extremely strong acceleration

- Doppler cooling

velocity v of the atom leads to Doppler shift of the laser frequency :

$$\omega_L \longrightarrow \omega_L - \vec{k}_L \cdot \vec{v}$$
$$\delta \longrightarrow \delta - \vec{k}_L \cdot \vec{v}$$

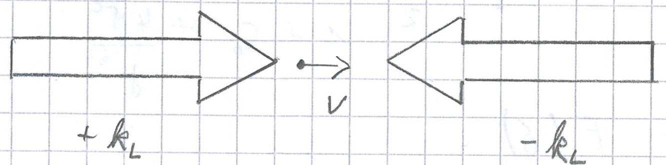
$$\hookrightarrow \quad \vec{F}(\delta) = \vec{F}(\delta(\vec{v})) = \vec{F}(\vec{v}) =$$

$$= \hbar \vec{k} \, \frac{\gamma/2 \cdot s_0}{1 + s_0 + \left(\frac{2(\delta - \vec{k}_L \cdot \vec{v})}{\gamma} \right)^2} , \qquad (13.2.)$$

velocity-dependent force on the atom !!

- Optical molasses (discussion in 10)

  - use two counter-propagating laser fields which are detuned with respect to the atomic resonance.



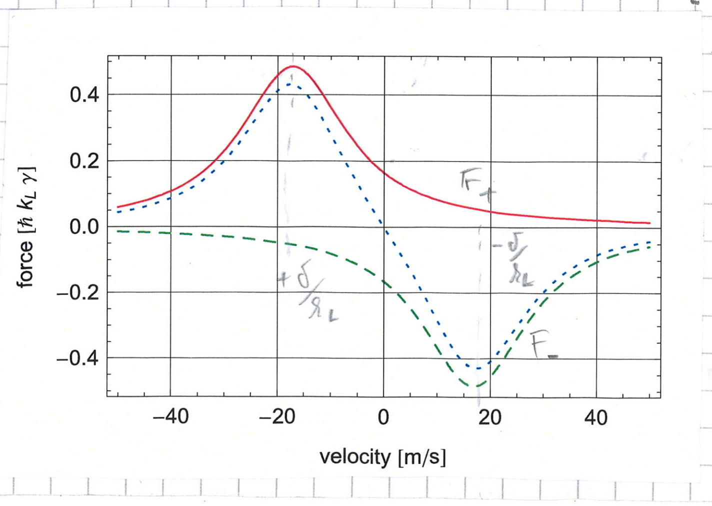
force of the two individual laser fields :

$$F_{\pm} = \pm \hbar k_L \frac{\gamma/2 \cdot s_0}{1 + s_0 + \left(\frac{2(\delta \mp k_L \cdot v)}{\gamma} \right)^2}$$

$(\gamma, \Omega_0, \delta) / 2\pi =$

$(5, 20, -20)$ MHz

Gesamtkraft: $F_+ + F_-$



- close to $v = 0$: linear regime,

$$F_{tot} \approx -\beta \cdot v \quad \text{with}$$

(13.5.) $$\beta = -\frac{8 \hbar k_L^2 \delta s_0}{\gamma \left(1 + s_0 + \left(\frac{2\delta}{\gamma}\right)^2\right)^2}$$

- F_{tot} corresponds to a friction force with coefficient β
- atoms are decelerated as in a viscose fluid
  -> optical molasses

• What sets the final temperature of this cooling method?
  - spontaneous emission leads to momentum transfers with random direction -> diffusive motion -> heating

    ↳ equilibrium Temp. between molasses cooling and heating due to spontaneous emission:

$$\underline{T_D = \frac{\hbar \gamma}{2 k_B}} \quad \text{Doppler-Temp.}$$

k_B ← Boltzmann's const.

e.g. $\approx 240\ \mu K$ for Na atoms (Na: sodium)

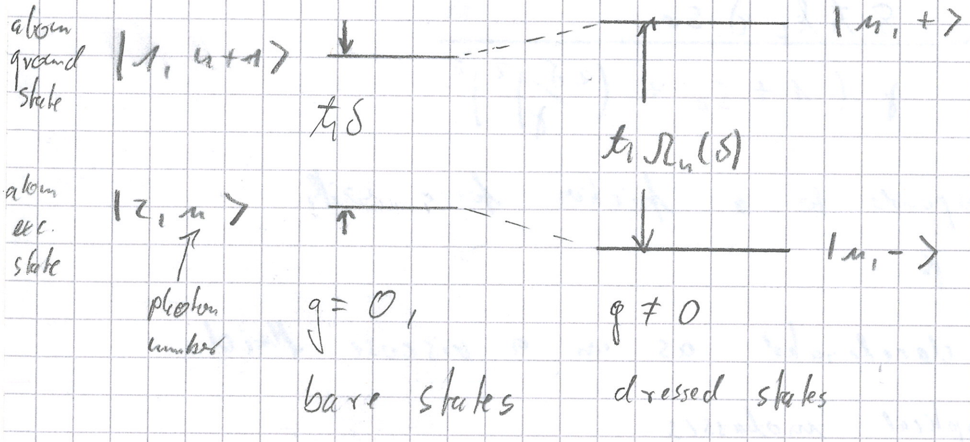
11.2 <u>AC-Stark shift / light shift and Sisyphus cooling</u>

• Laser-cooled clouds with $T < T_D$ have been experimentally observed. How is this possible?

→

AC Stark shift

- Recall chap. 4.3, Dressed-state picture: two-level atom in a light field (here: blue-det.)



g: coupling strength

$$g = -\frac{d \cdot \varepsilon_0}{\hbar}$$

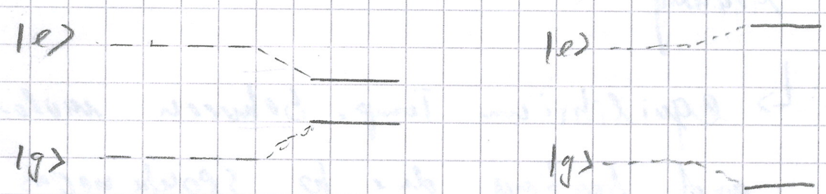
(single-photon Rabi freq.)

Energy shift: $\Delta E^{\pm} = \pm \hbar \dfrac{g^2 (n+1)}{\delta} \underset{\text{semi-klassisch}}{\approx} \pm \dfrac{\hbar \Omega^2}{\delta}$

↳ energy levels shift in detuned laser fields

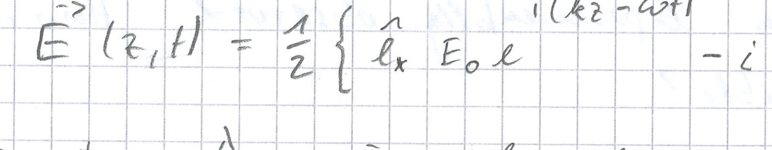
- $\delta > 0$ (blue-det.) $\qquad \delta < 0$ (red-det.)

simplest case: $\Delta E \sim \dfrac{\gamma}{\delta} \cdot$ Int.



Sisyphus-Cooling

- $T < T_D$ was only observed for particular polarizations of the light fields used for laser cooling and particular atomic transitions
e.g. lin ⊥ lin

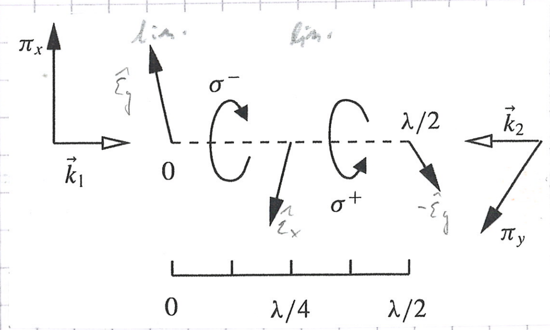


- electric field:

$$\vec{E}(z,t) = \frac{1}{2}\left\{ \hat{e}_x E_0 e^{i(kz-\omega t)} - i \hat{e}_y E_0 e^{i(kz+\omega t)} \right\}$$

für $z = \pm n \cdot \frac{\lambda}{2}$ $\quad \sigma^-$ - polarized

für $z = \left(\frac{1}{4} \pm n\right) \cdot \frac{\lambda}{2}$ $\quad \sigma^+$ - polarized



$\vec{E}(z,t) = \frac{1}{2}\left\{\vec{\varepsilon}(z)\, E\, e^{i\omega t} + c.c.\right\}$

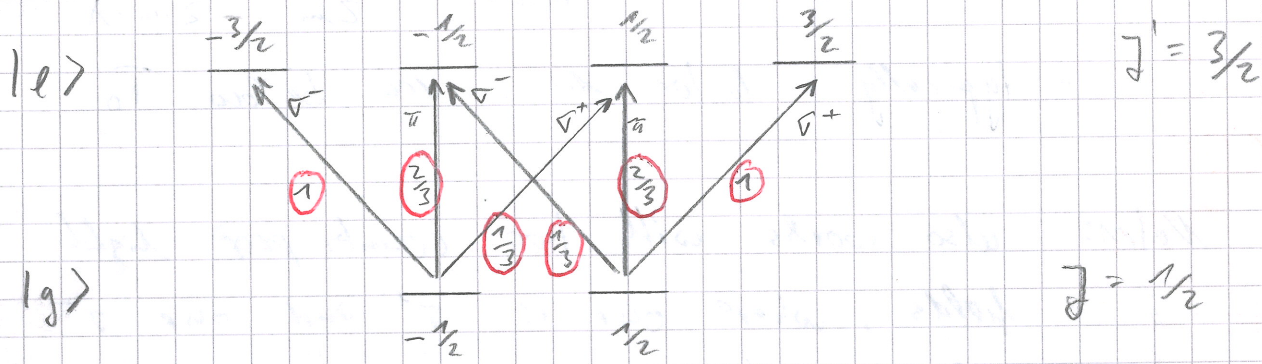
where $\vec{\varepsilon}(z)$ is a position-dependent polarization vector

→ Polarization gradient

(13.8.) $$\vec{\varepsilon}(z) = \vec{e}_- \cos(k \cdot z) - i\, \vec{e}_+ \sin(kz)$$

(13.9.) $$\vec{e}_\pm = \pm \frac{1}{\sqrt{2}} \left\{ \vec{e}_x \mp i\, \vec{e}_y \right\}$$

- suitable multi-level atom:
  - must show different coupling to these polarizations

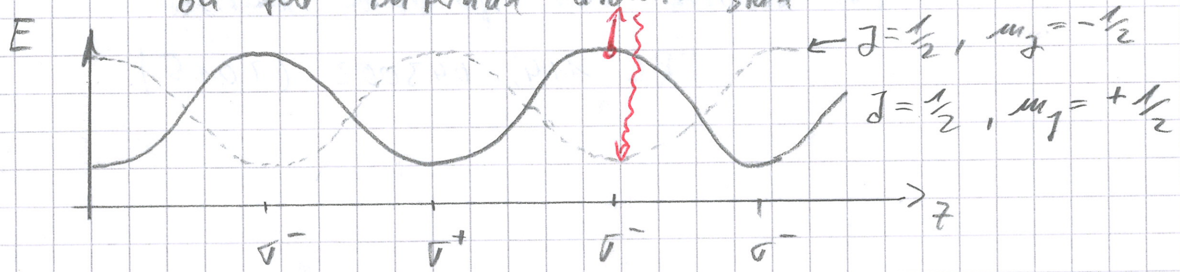


○ : Transition strength

- for an atom in a given ground state, the coupling and, thus, the light shift depends on the local polarization of the light
- for a given polarization, the shift depends on the internal atomic state

⇒

for red.-detuned field:



↳ position-dependent AC-Stark shift

↳ and: optical pumping transfers atoms always from "top of the hill" to "bottom of the valley" →

- optical pumping

σ^+-pol. regions : atom pumped to $m_J = +1/2$

σ^- — " — $m_J = -1/2$

- atom always moves "up-hill" and, in this way, loses kinetic energy ("Sisyphus-cooling")

- Minimum temperature is given by the momentum kick from the last emitted photon:

$$k_B \cdot T \sim \hbar \omega_{recoil} \sim \frac{\hbar^2 k^2}{2m} = \frac{h^2}{2 \cdot m \cdot \lambda^2} \qquad (13.10)$$

- typically a factor 10 ... 100 below T_D

Note 1: also works with two counter-prop. light fields, where one is σ^+ and one σ^- polarized. (much more complicated, see Dalibard J. Opt. Soc. Am. B 6, 2023 (1989))

Note 2: Spont. Em. not necessarily isotropic, e.g. for atoms close to surfaces

Note 3: ◦ believed for a long time that laser cooling requires spontaneous emission (entropy argument)

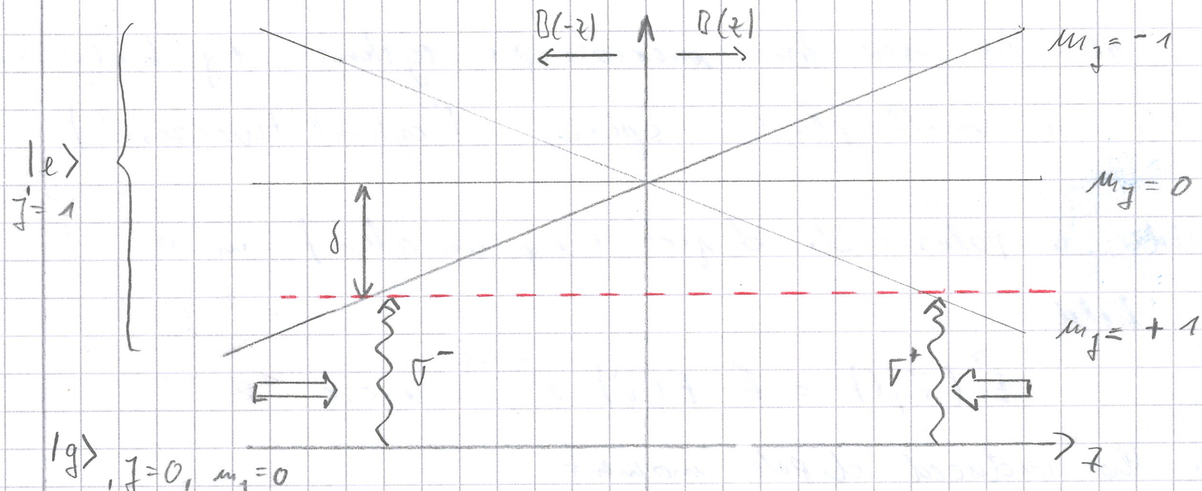
But since very recently "Laser cooling w/o spontaneous emission" PRL 114, 043002 (2015)

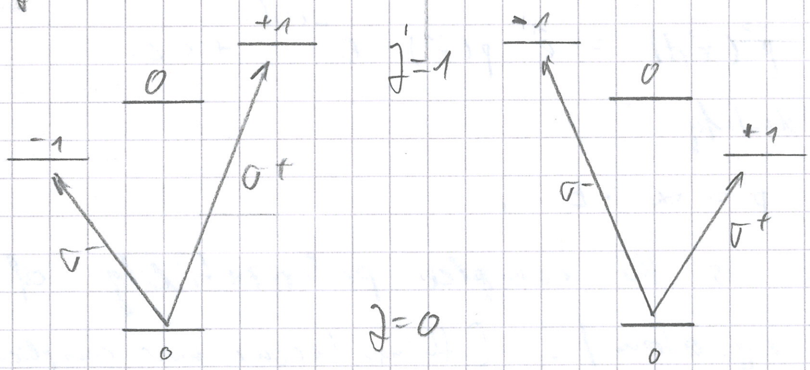
→ 11.3. <u>Magneto-Optical Trap (MOT)</u> (in 1D)

- not only cool atoms but also keep them at a fixed position

- combine laser cooling with pos.-dependent force:
  - magnetic field in order to have a position-dependent shift of the atomic energy levels
  - suitable polarization of the lasers

- quadrupol-field: $B(z) = A \cdot z$





As soon as atoms diffuse out of the center of the trap, they are tuned into resonance which pushes them back to the center. → Trapping mechanism.

→

11.4. AC-Stark Shift / Dipole trap / optical tweezer

- so far, only dissipative traps, which e.g. do not allow storing superposition states (as spontaneous emission is incoherent)

  → no dynamics according to Schrödinger's eq. observable (e.g. Rabi osc., optical storage, etc.)

- solution: - conservative trap, i.e. traps which can be described as a potential
  - two main types:

    optical dipole trap & magnetic trap

Classical description of optical dipole traps

- can also be used for macroscopic systems, e.g. biological cells or small plastic spheres ("optical tweezers")

Consider a polarizable object (e.g. an atom) in a laser field

$$\vec{E}(\vec{r},t) = \hat{e}\, E(\vec{r})\, e^{-i\omega t} + c.c. \qquad 13.11.$$

with the induced dipole moment

$$\vec{p}(\vec{r},t) = \hat{e}\, p(\vec{r})\, e^{-i\omega t} + c.c. \qquad 13.12.$$

We can identify

$$p = \alpha \cdot E, \qquad 13.13.$$

where α is the complex polarizability of the object (e.g. atom). [things become more complicated for arb. polarized field and multi-level atoms]

- The interaction potential is

$$U_{dip} = -\frac{1}{2}\langle \vec{p}\cdot\vec{E}\rangle = -\frac{1}{2\varepsilon_0 c}\,\mathrm{Re}(\alpha)\cdot J, \qquad 13.14$$

where $J = 2\varepsilon_0 c\,|E|^2$ (intensity).