Foot: Atomic Physics

Laser cooling and trapping

velocity is bad for precision laser spectroscopy

Dopple shift $\propto \frac{v}{c}$ → shifts / broadens resonance lines

2nd order Doppler $\propto \frac{v^2}{c^2}$ → relativistic eigen times

Time-of-flight broadening (finite interaction time atom-light)

↓

transit time broadening → $\Gamma_{TTB} \sim \frac{\mathcal{O}(1)}{T}$

⇒ need cold, slow atoms, best = trapped

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COOLING OF GASES BY LASER RADIATION[1*]

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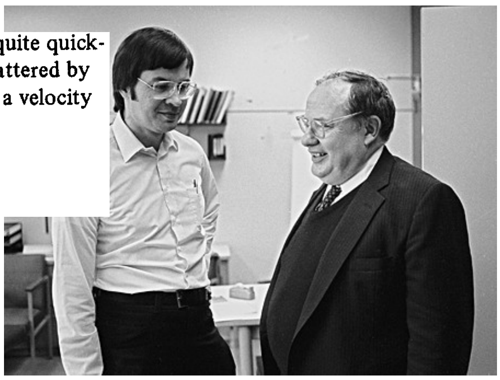
It is shown that a low-density gas can be cooled by illuminating it with intense, quasi-monochromatic light confined to the lower-frequency half of a resonance line's Doppler width. Translational kinetic energy can be transferred from the gas to the scattered light, until the atomic velocity is reduced by the ratio of the Doppler width to the natural line width.

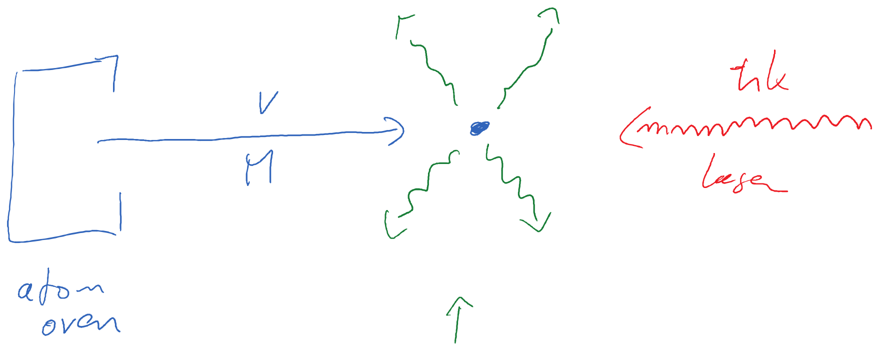
Cooling of this order could be achieved quite quickly. When a photon of momentum $h\nu/c$ is scattered by an atom of mass M, moving towards it with a velocity v, the average change in velocity is

$$\Delta V = \frac{\Delta(Mv)}{M} - \frac{h\nu}{Mc}.$$



photons: energy $E = \hbar\omega$

momentum $p = \hbar k$



emission: momenta average to 0

$\overleftarrow{\quad F_{scatt} \quad}$

$$F_{scatt} = \hbar k \cdot \Gamma \cdot \rho_{22}$$

photon momentum

scattering rate

$$\gamma_{ph} = \frac{S_0}{1+S_0} \cdot \frac{\Gamma/2}{1 + 4\delta^2/\Gamma'^2}$$

power-broadened Lorentzian

$$\Gamma' = \Gamma\sqrt{1+S_0}$$

$$\gamma_{ph}^{max} = \frac{\Gamma}{2}$$

$$F = Ma \longrightarrow a_{max} = \frac{\hbar k \Gamma}{2M} = \frac{v_r}{2\tau}$$

e.g. Na $\quad \tau = 16\,ns \quad \lambda = 589\,nm$

$M = 23u$

$v_r = 3\,cm/s$

$$a_{max} = 9 \cdot 10^5\, m/s^2 = 10^5 g$$

slowing down changes Doppler shift

$\Rightarrow$ atom is out of resonance

→ no more slowing

- **chirp cooling**

increase laser frequency as atom decelerates

$$-\dot{\omega}_{Laser} \approx \dot{\omega}_D = \vec{k}\cdot\vec{a} = \frac{\hbar k^2 \Gamma}{2M} = \omega_r \cdot \Gamma$$

recoil frequency $\omega_r = \frac{\hbar k^2}{2M}$

⊖ several GHz in few ms = difficult

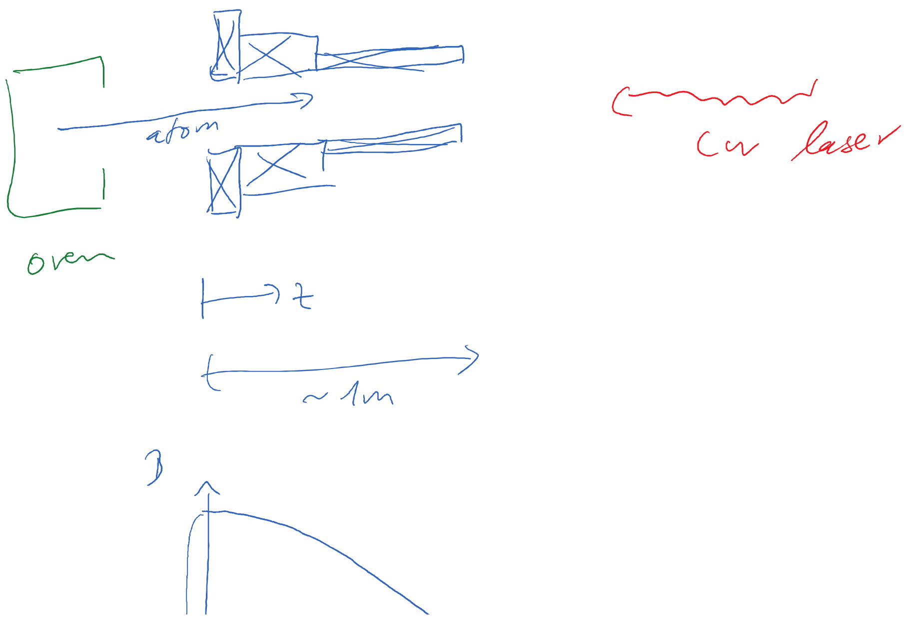
⊖ only pulsed operation

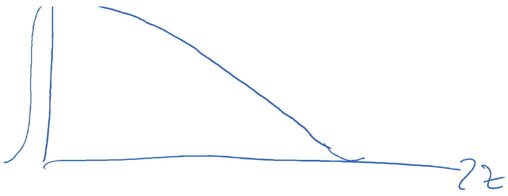
- **Zeeman slower**

(Bill Philips Nobel 1997)

position-dependent magnetic field shifts

→ —"— resonance frequency





constant deceleration $a = \eta \cdot a_{max}$ $\eta < 1$

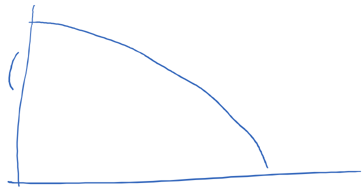
$$\frac{dv}{dt} = v\frac{dv}{dx} = -a$$

$$v_0^2 - v^2 = 2az$$

$$L = \frac{v_0^2}{\eta\, a_{max}}$$

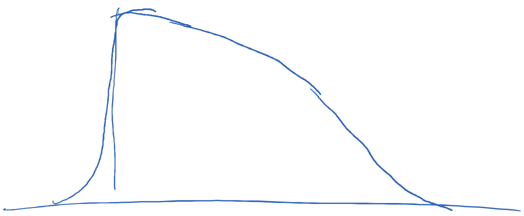
$$B(z) = B_0\sqrt{1 - \frac{z}{z_0}}$$

ideal

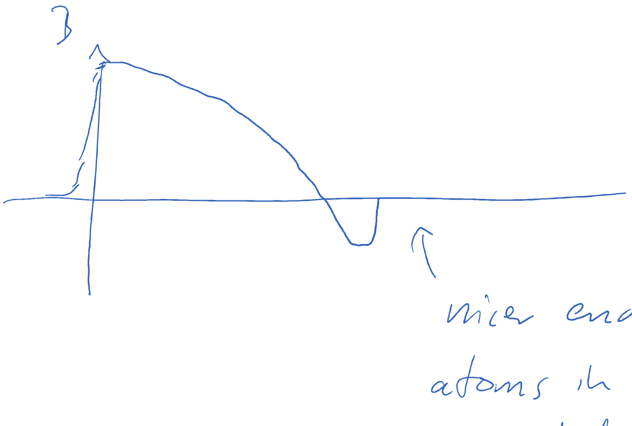


$$z_0 = \frac{M v_0^2}{\eta \hbar k \Gamma} = \text{length of magnet}$$

real



better : spin-flip slower

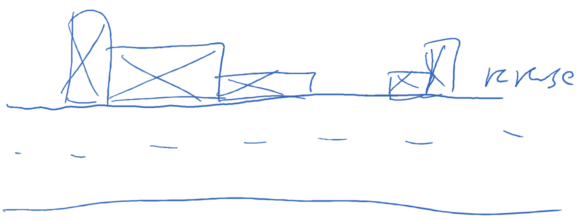


$\sqrt{z}$ + DC offset

nicer end

atoms in field-free region do not interact w/ laser

... w/ laser



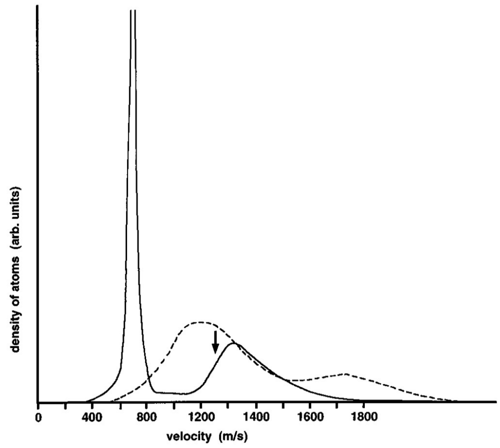
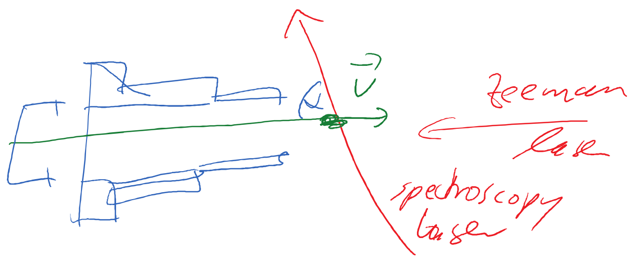


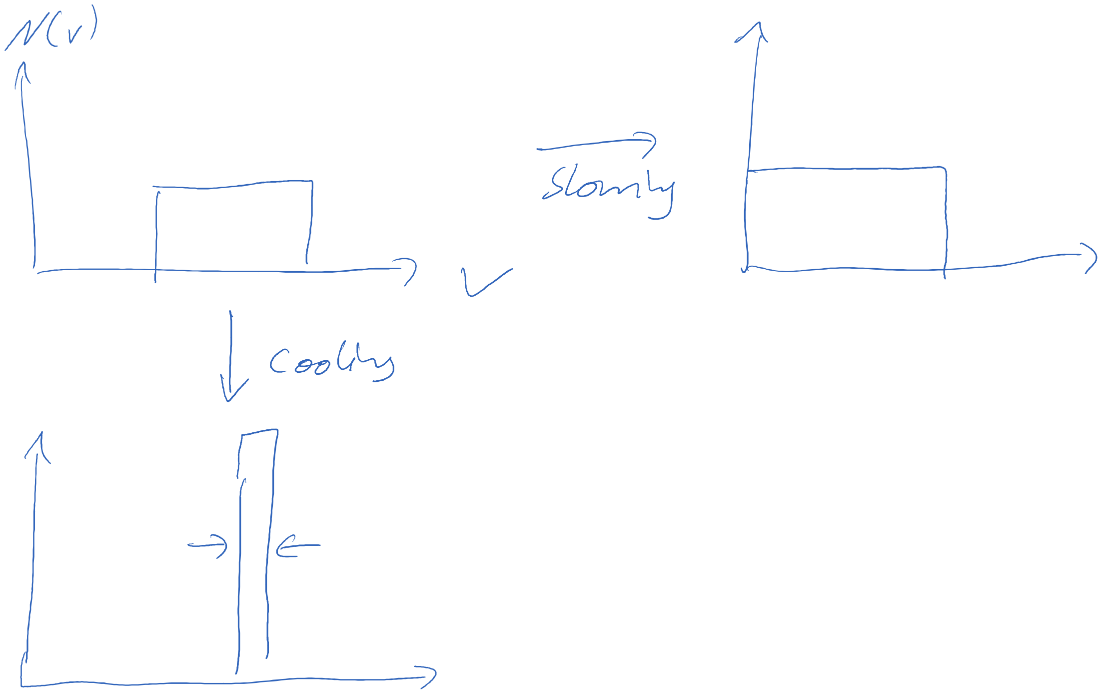
FIG. 5. Velocity distribution before (dashed) and after (solid) Zeeman cooling. The arrow indicates the highest velocity resonant with the slowing laser. (The extra bump at 1700 m/s is from $F=1$ atoms, which are optically pumped into $F=2$ during the cooling process.)

Bill Philips Nobel lecture (Rev. Mod. Phys.)



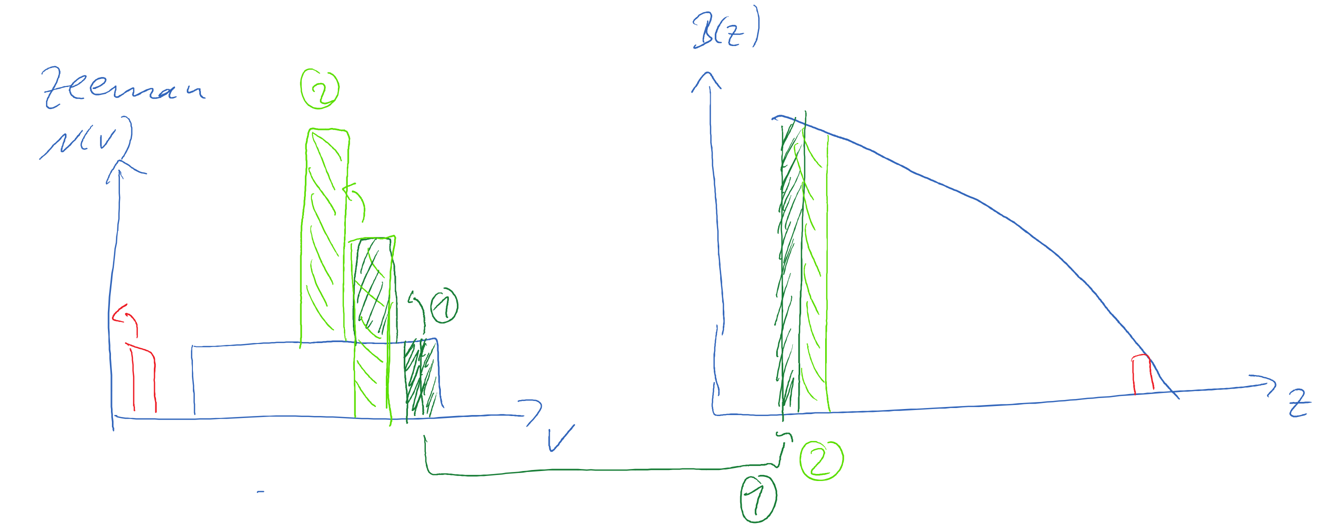
Doppler effect $= \vec{v} \cdot \vec{k}_{spectroscopy}$

slowing vs. cooling



fast but cold!

B(z)



Temp. = defined for

closed system in equilibrium

$\neq$ atom + laser

We just claim:

$$\frac{1}{2} k_B \cdot T = \langle E_k \rangle \quad \text{avg. } E_{kin} \text{ in 1D}$$

- critical temp.

  Doppler shift small enough for interaction w/ laser

  $$v_c = \frac{\Gamma}{k} \sim 1\, m/s$$

$$k_B \cdot T_C = \frac{M\Gamma^2}{k^2} \qquad \text{few mK}$$

- Doppler temperature

$\hat{=}$ nat linewidth

$$k_B \cdot T_D = \frac{\hbar\Gamma}{2} \qquad \text{few } 100\,\mu K$$

"Doppler limit"

1D velocity $v_D = \sqrt{\frac{k_B \cdot T_D}{M}} \sim 30\,\mathrm{cm/s}$

- recoil temperature

1 photon recoil

$$v_r = \frac{\hbar k}{M} \sim 1\,\mathrm{cm/s}$$

$$k_B T_r = \frac{\hbar^2 k^2}{M} \sim \mu K$$