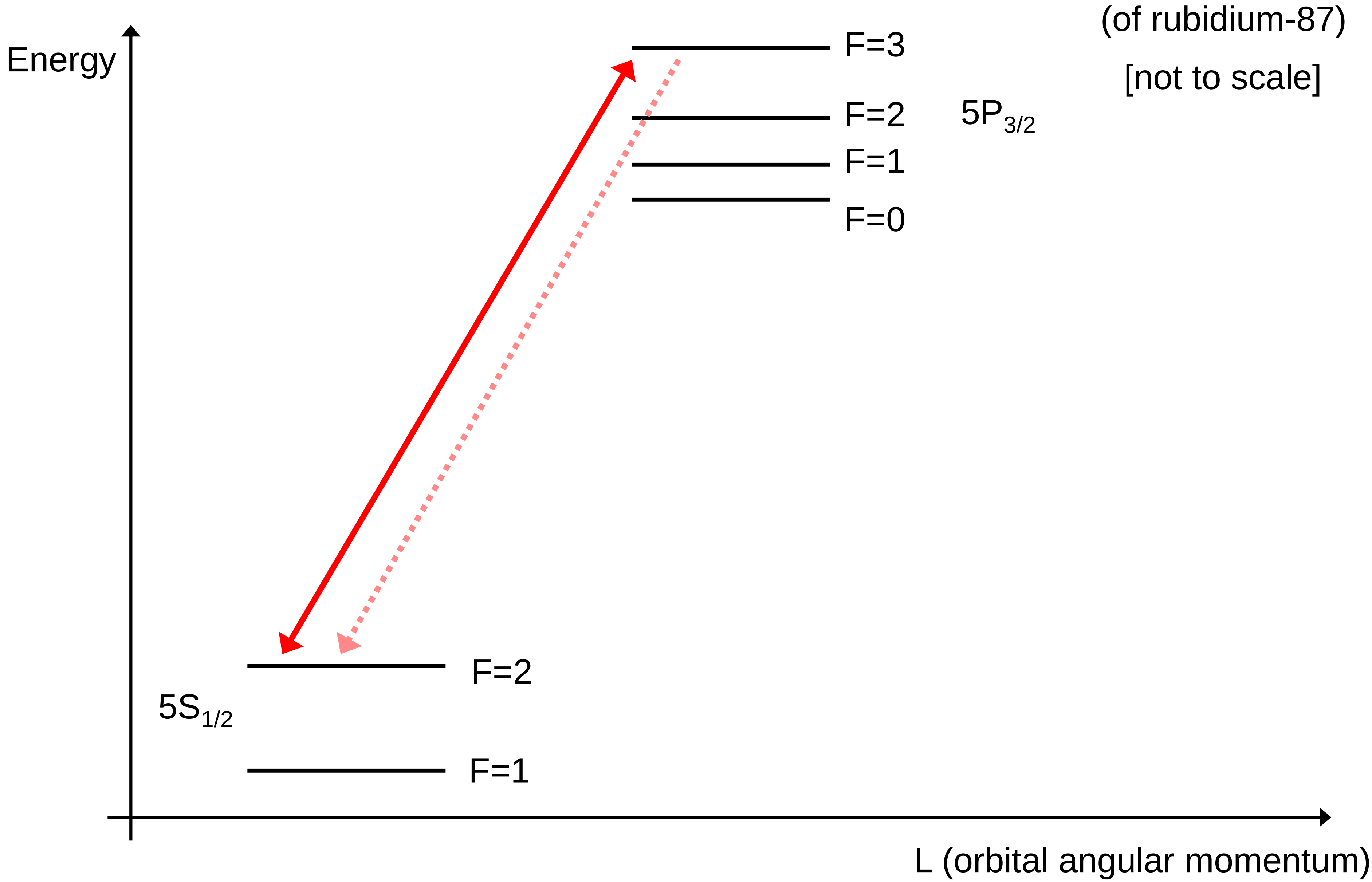
There are no 2-level atoms
and cesium isn't one of them !!!

Attributed to Bill Phillips
Nobel Prize in Physics (1997) for laser cooling

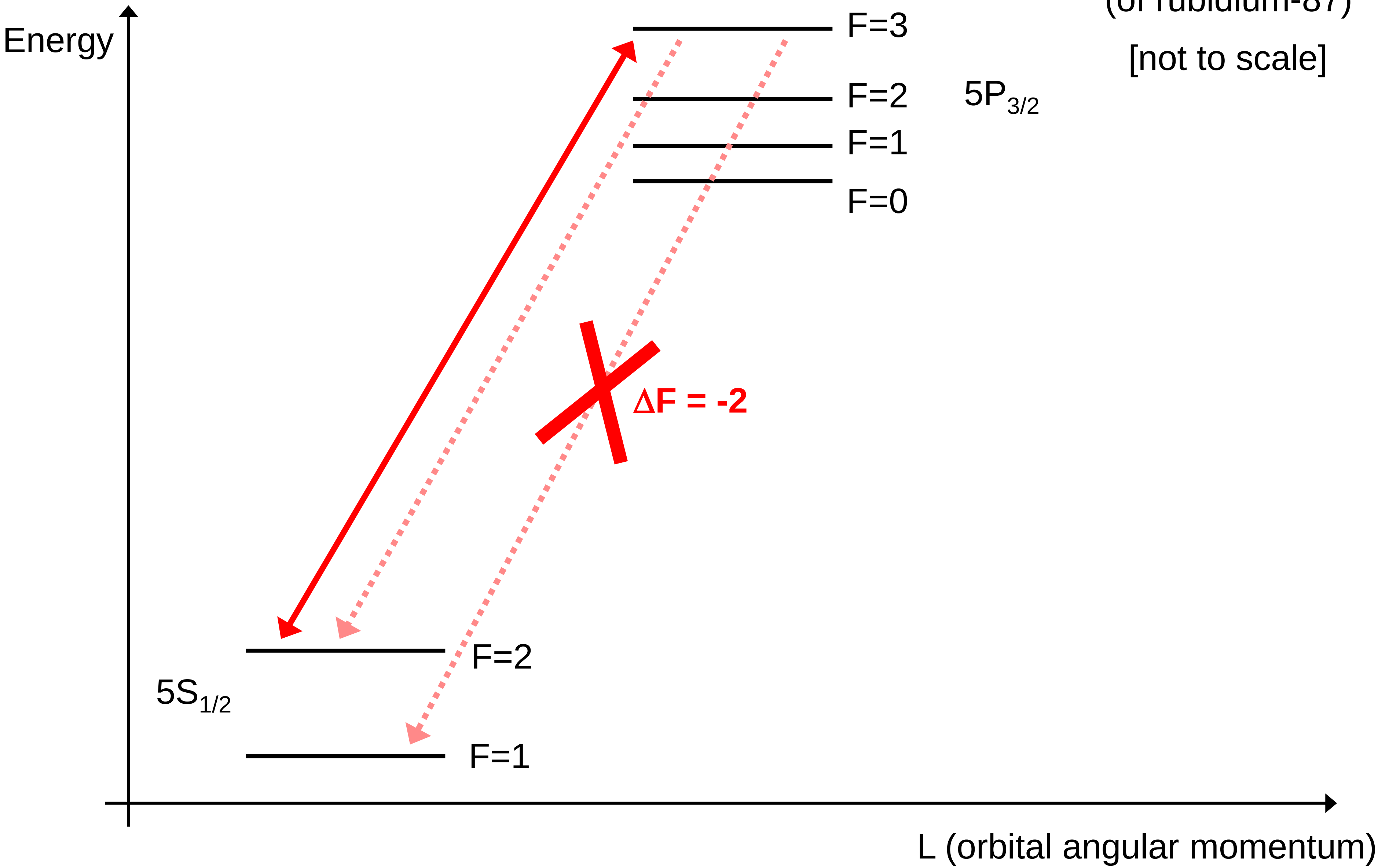
Why are Alkalis "2-level atoms" ?



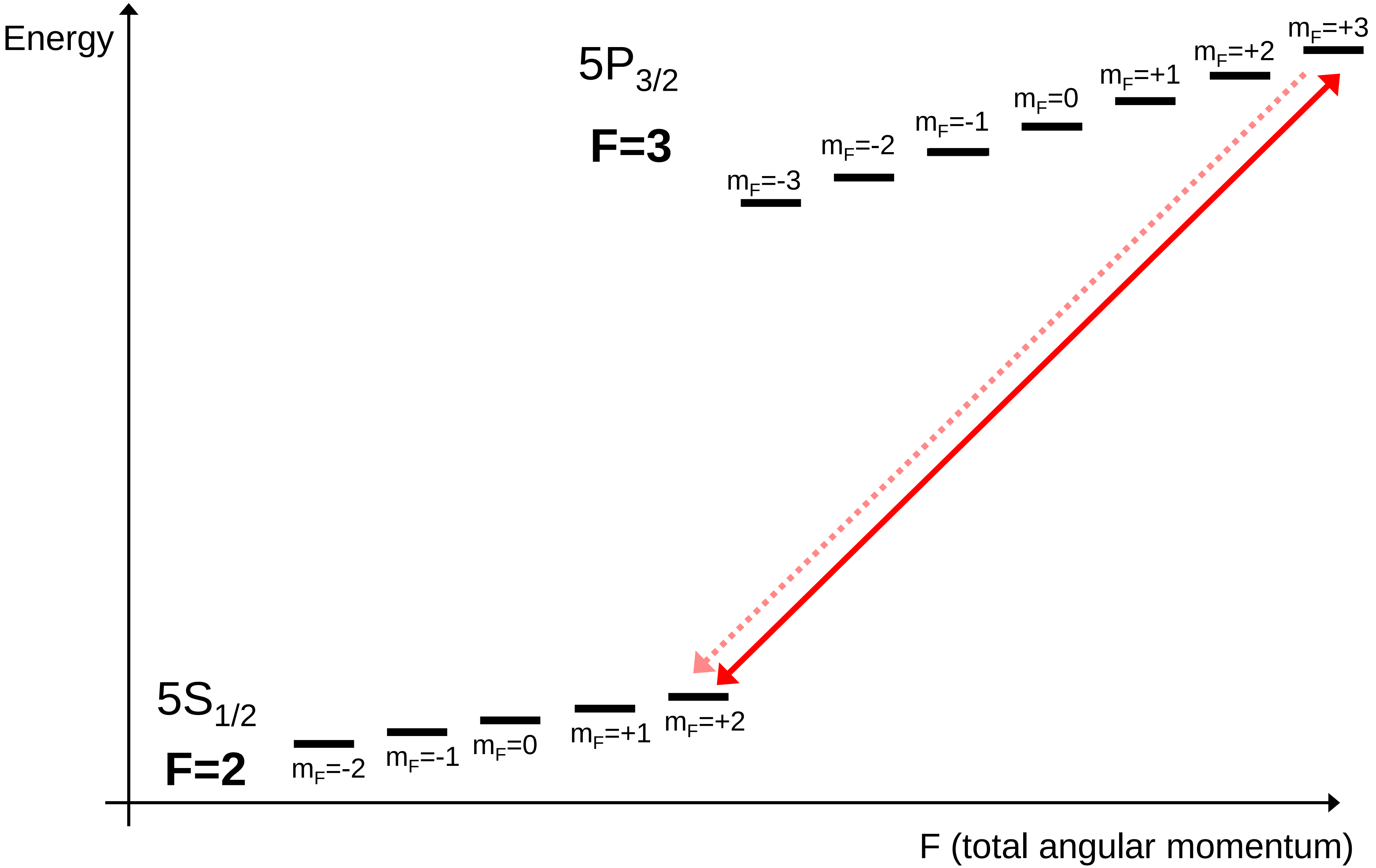
Why are Alkalis "2-level atoms" ?

(of rubidium-87)

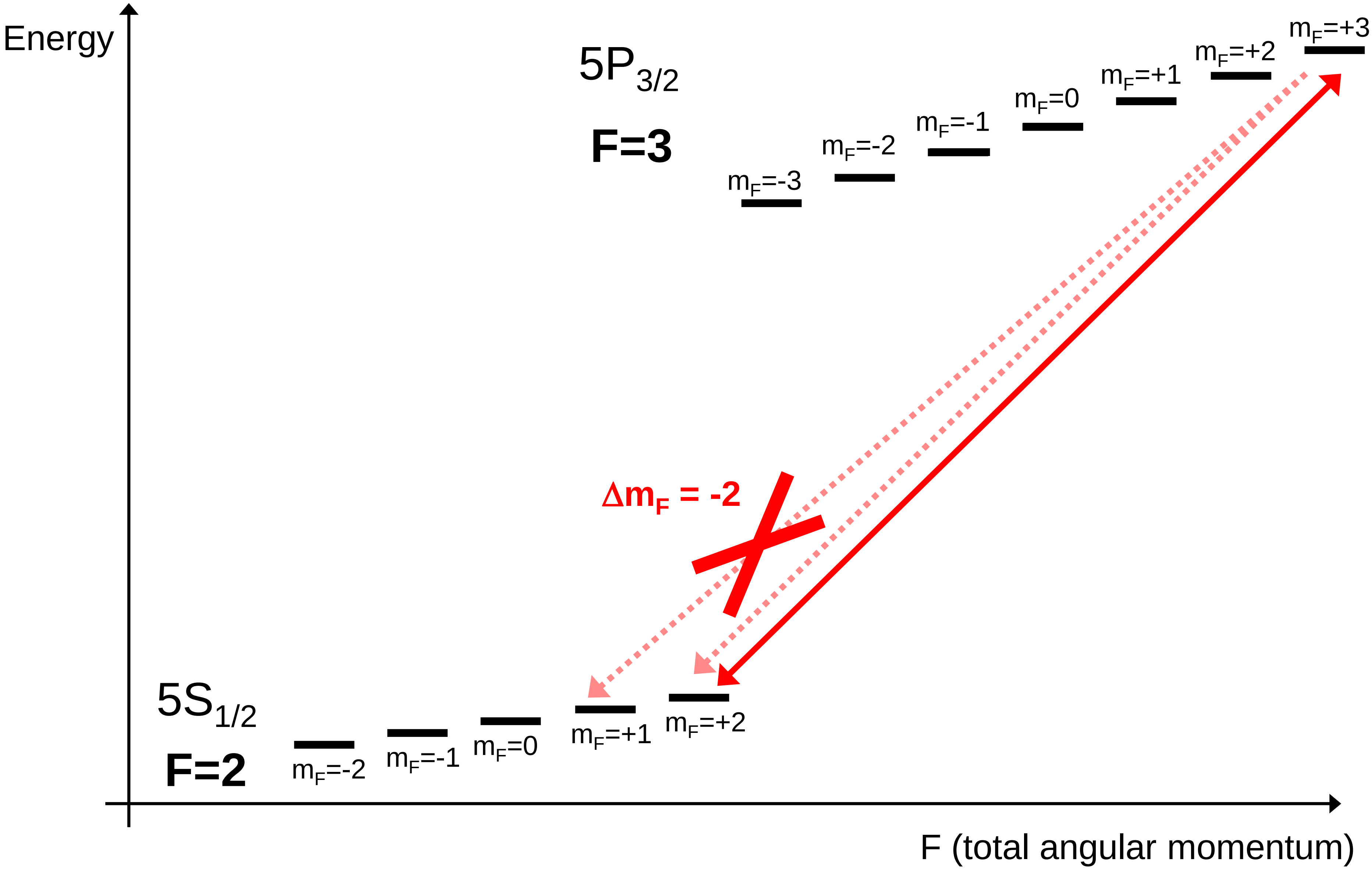
[not to scale]



The D2 line Cycling Transition



The D2 line Cycling Transition



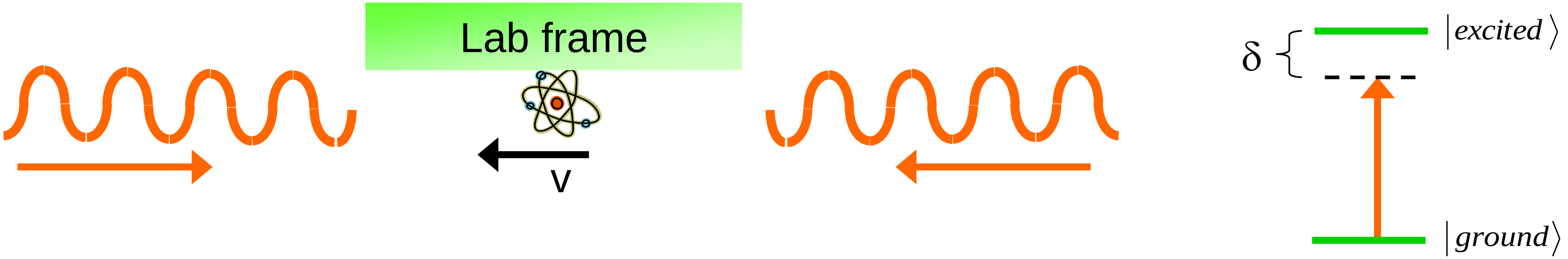
Laser Cooling

1. Doppler Cooling – optical molasses.

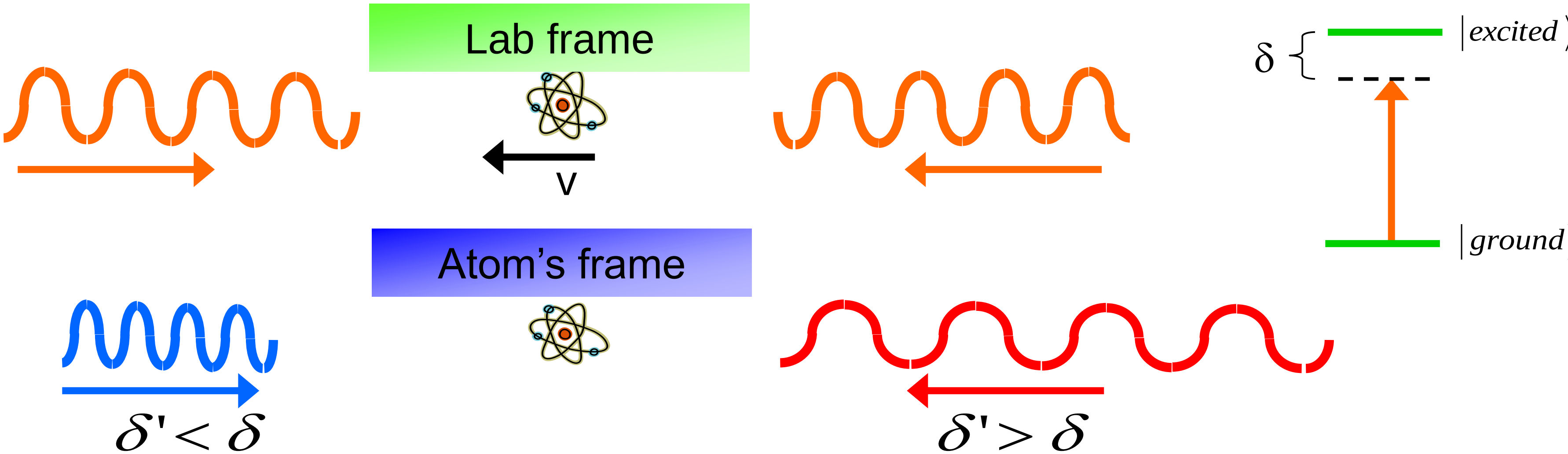
2. Doppler temperature.

3. Magneto-optical trap.

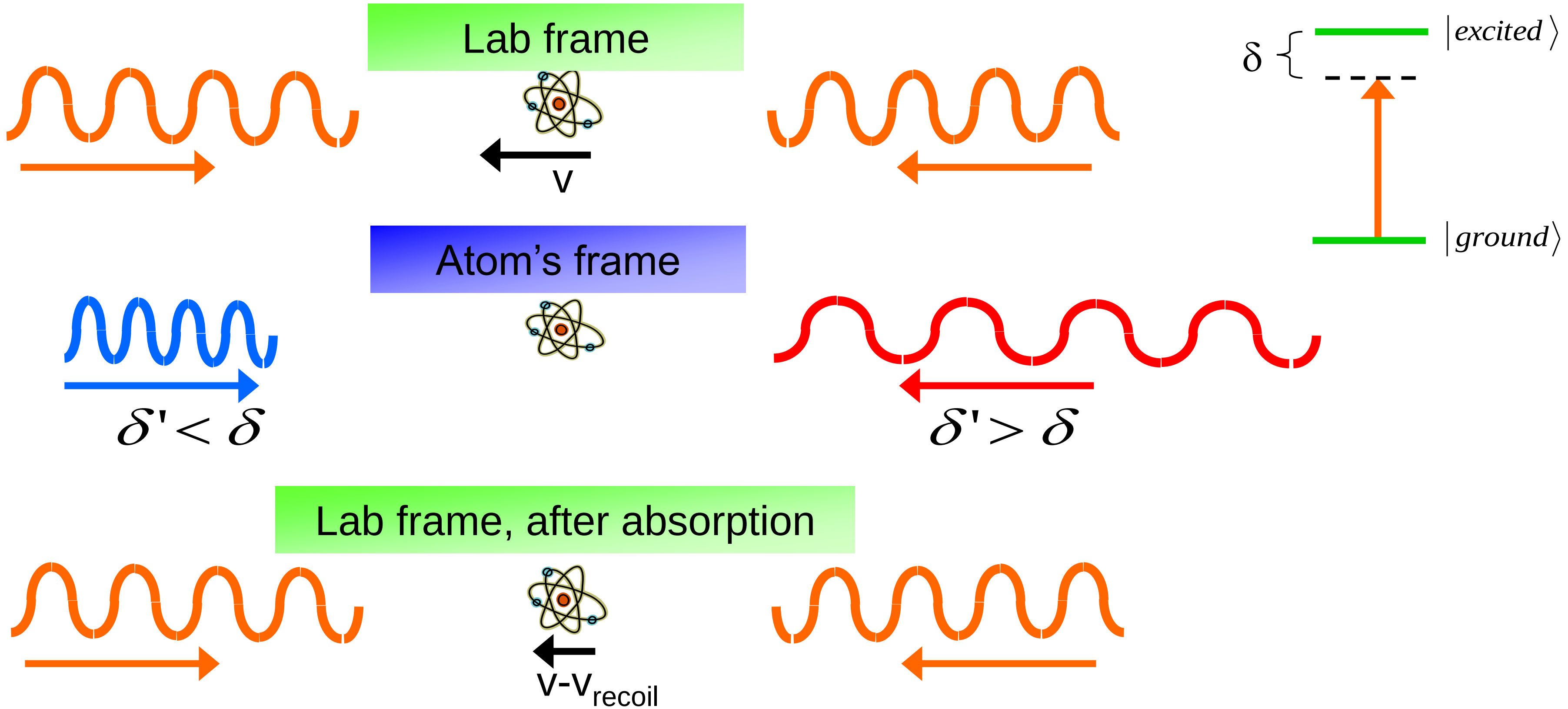
Doppler Cooling: How can a laser cool?



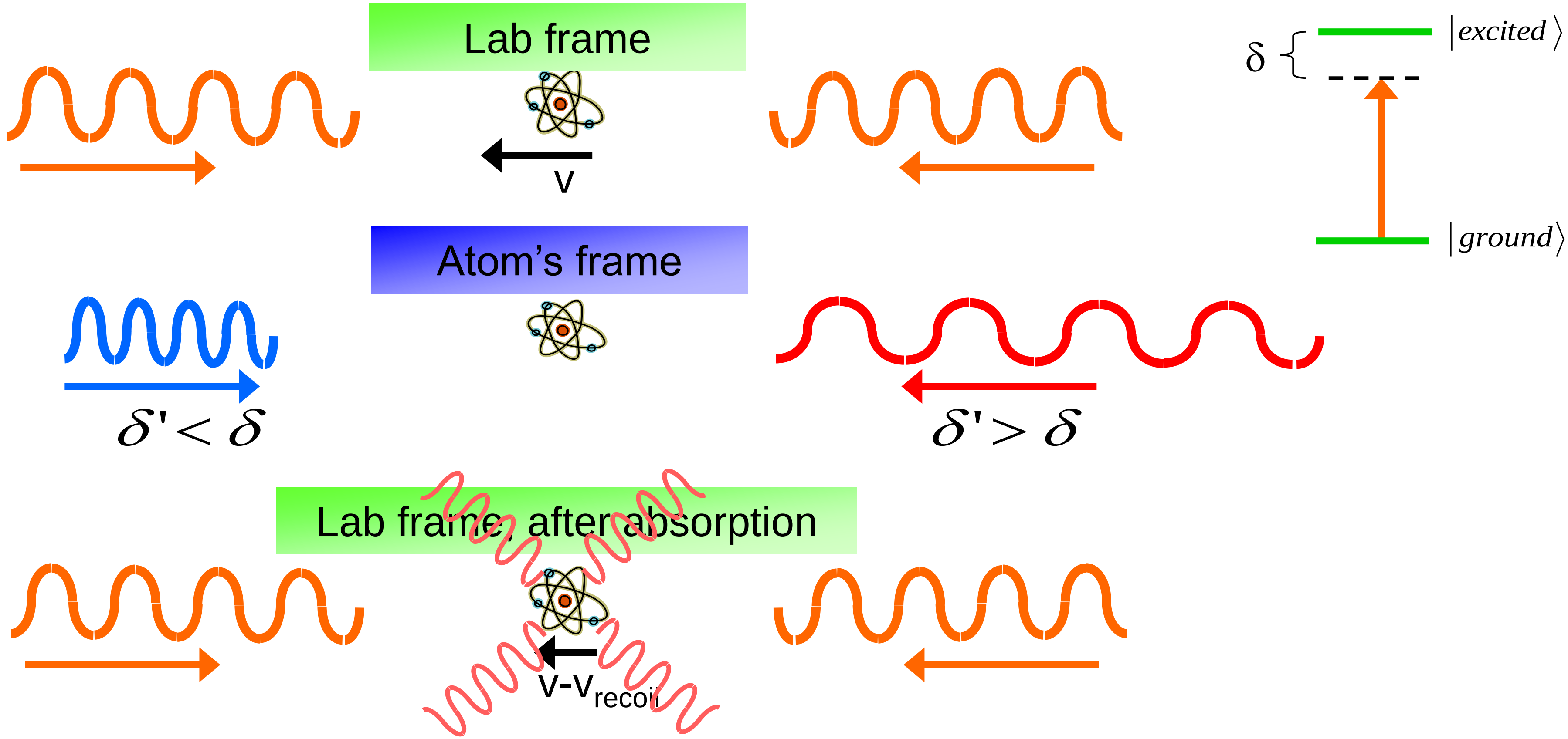
Doppler Cooling: How can a laser cool?



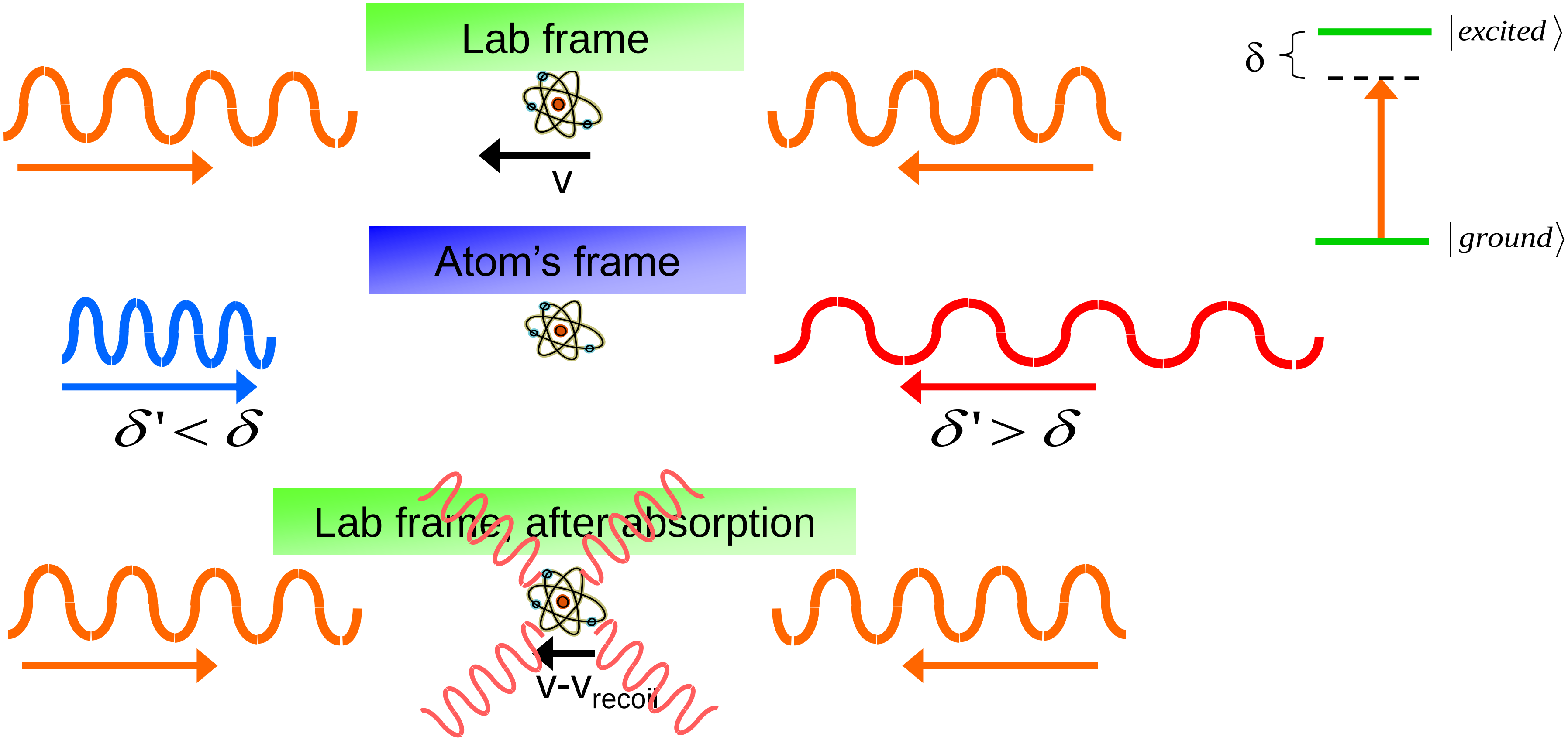
Doppler Cooling: How can a laser cool?



Doppler Cooling: How can a laser cool?

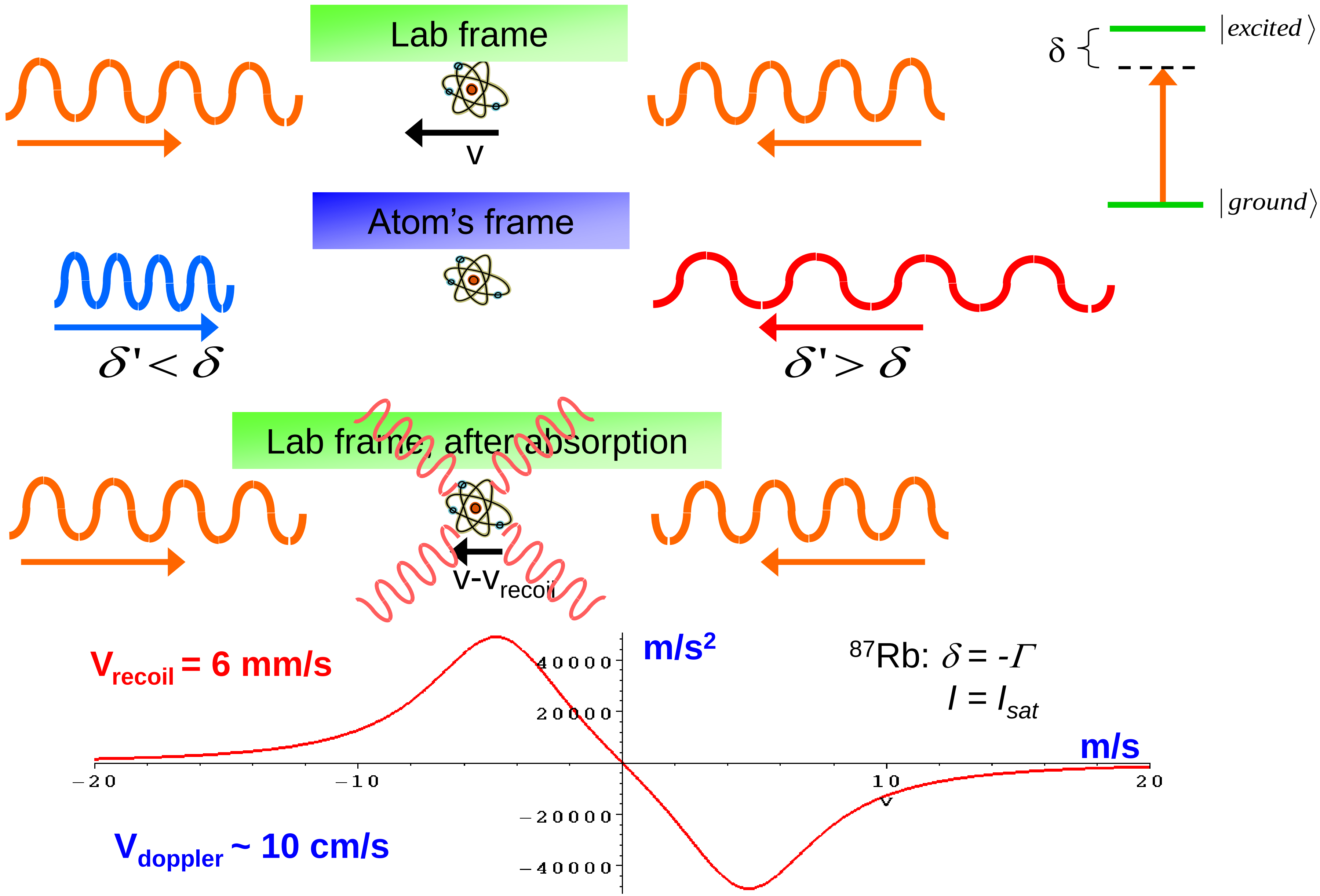


Doppler Cooling: How can a laser cool?



- Absorb a photon → atom gets $\hbar\vec{k}$ momentum kick.
- Repeat process at 10^7 kicks/s → large deceleration.
- Emitted photons are radiated symmetrically
  → do not affect motion on average

Doppler Cooling: How can a laser cool?



Magneto-Optical Trap (MOT)

Problem:

Doppler cooling reduces momentum spread of atoms only.

→ Similar to a damping or friction force (optical molasses).

→ Does not reduce spatial spread.

→ Does not confine the atoms.

Magneto-Optical Trap (MOT)

Problem:

Doppler cooling reduces momentum spread of atoms only.

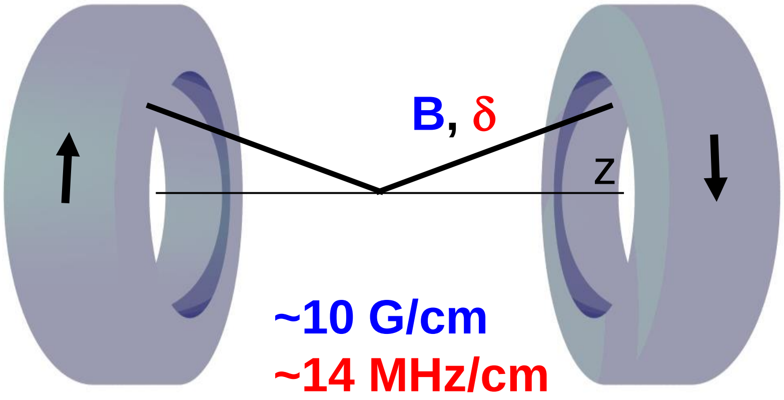
→ Similar to a damping or friction force (optical molasses).

→ Does not reduce spatial spread.

→ Does not confine the atoms.

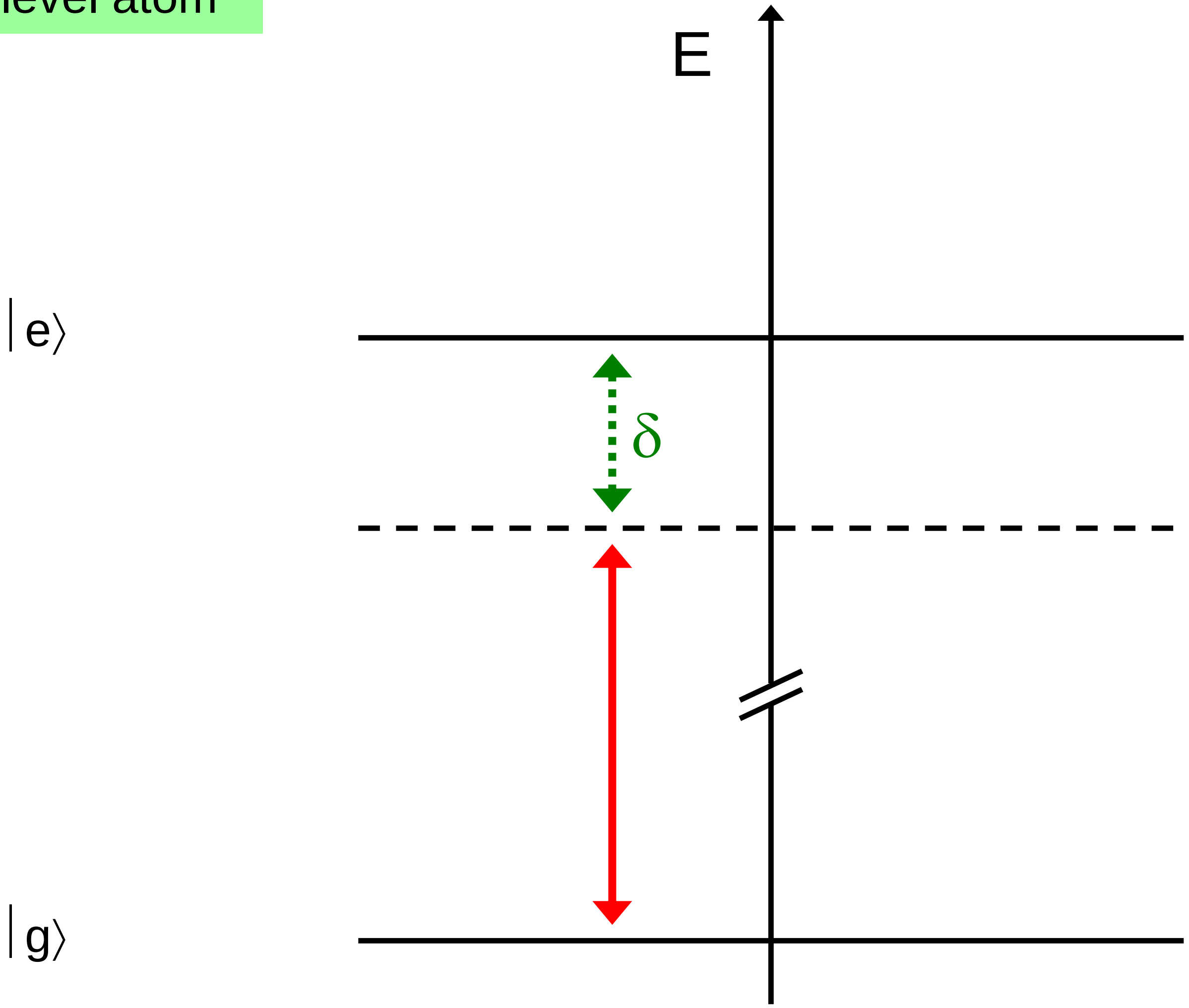
Solution:

Spatially tune the laser-atom detuning with the Zeeman shift from a spatially varying **magnetic field**.



Magneto-Optical Trap

2-level atom

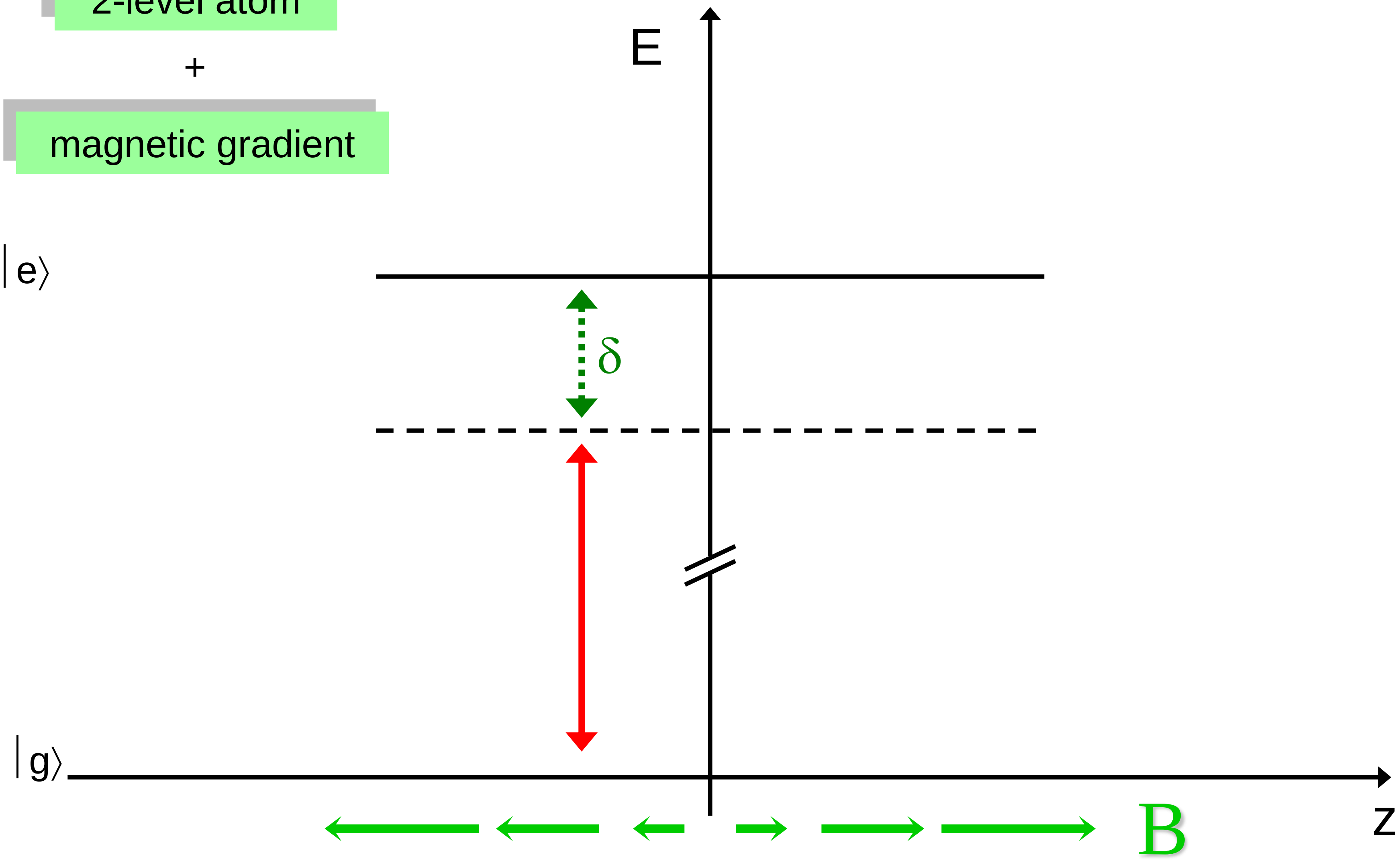


Magneto-Optical Trap

2-level atom

+

magnetic gradient



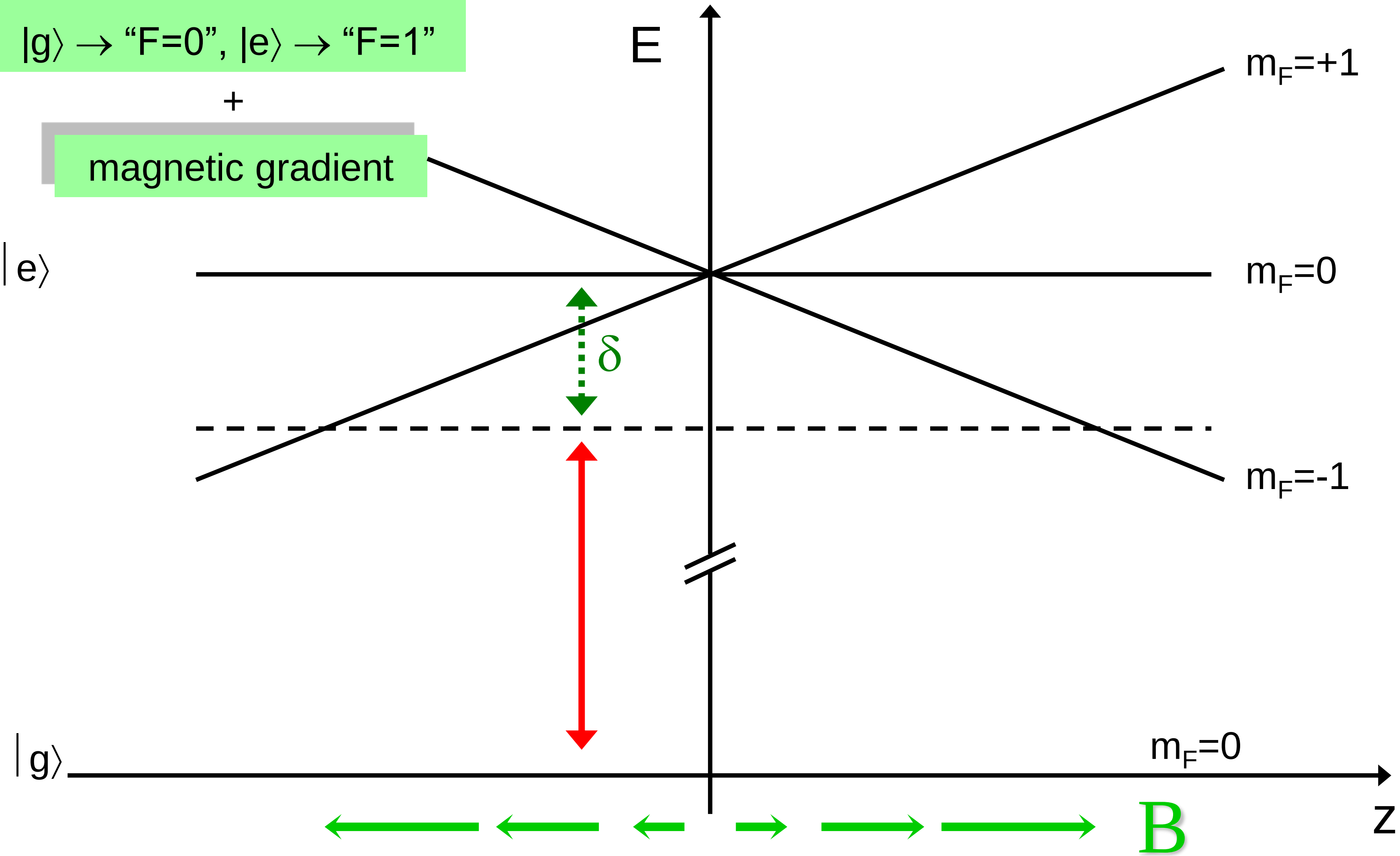
Magneto-Optical Trap

4-level atom

$|g\rangle \rightarrow$ “F=0”, $|e\rangle \rightarrow$ “F=1”

+

magnetic gradient



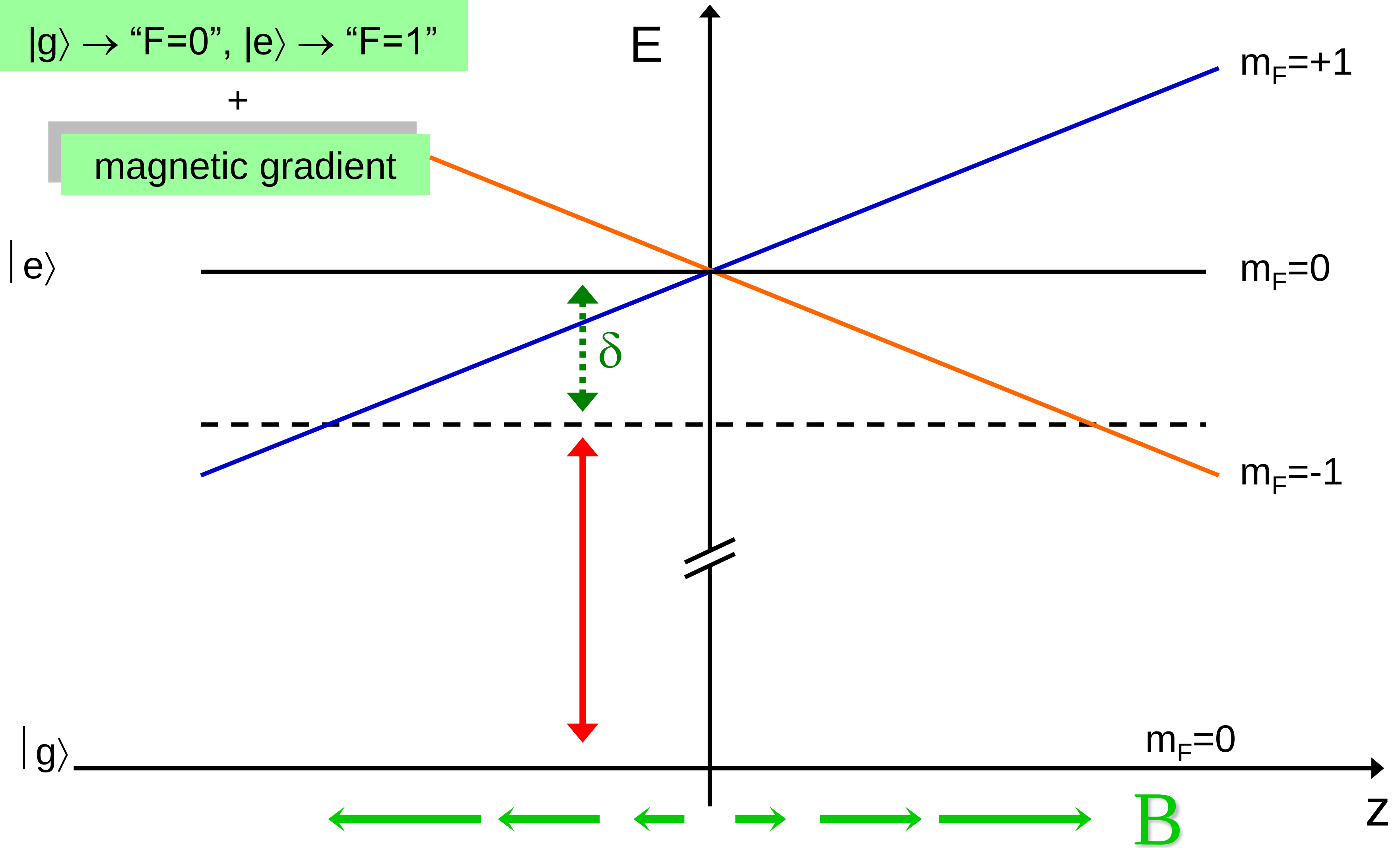
Magneto-Optical Trap

4-level atom

$|g\rangle \rightarrow$ "F=0", $|e\rangle \rightarrow$ "F=1"

+

magnetic gradient



Magneto-Optical Trap

4-level atom

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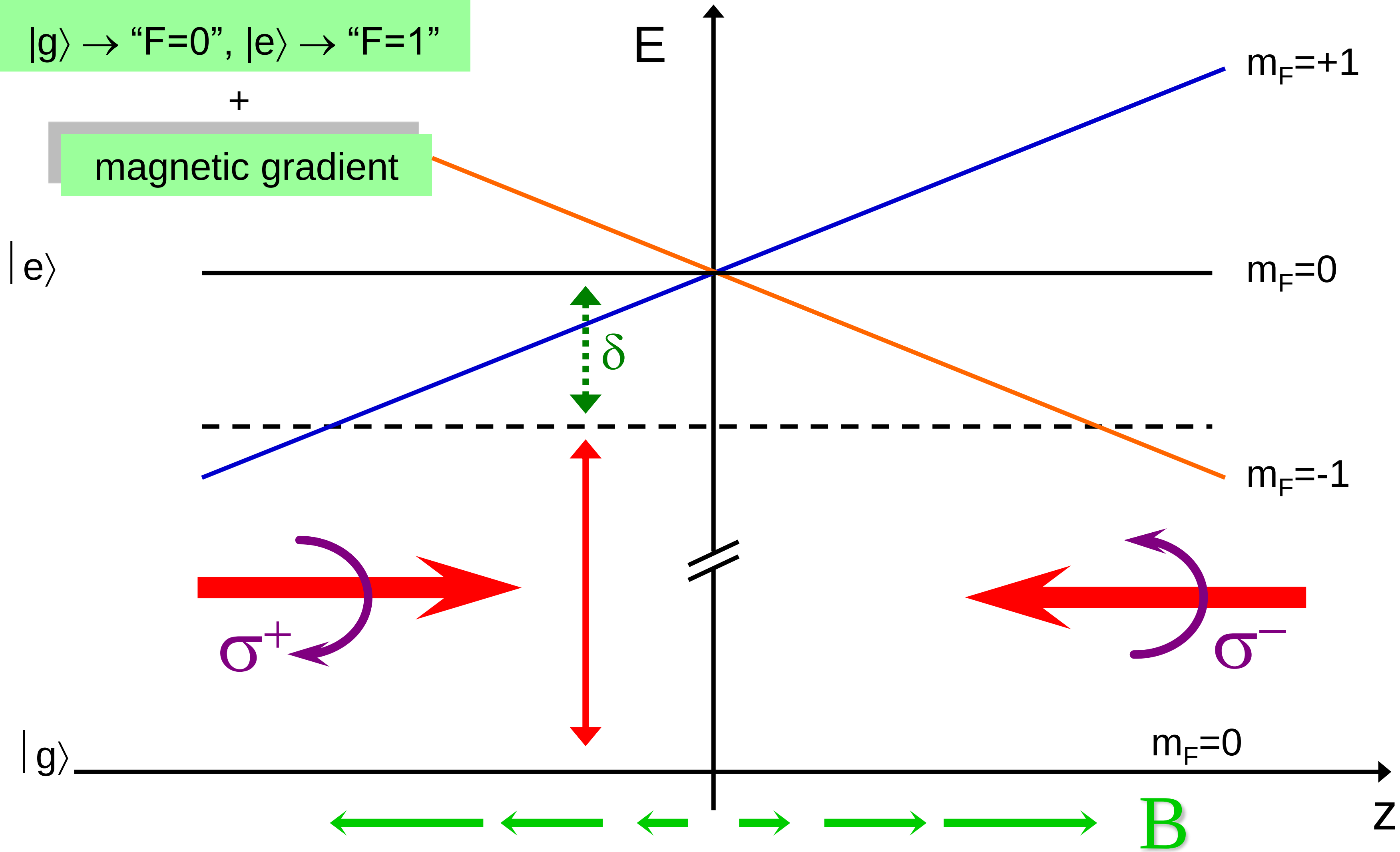
magnetic gradient



Magneto-Optical Trap

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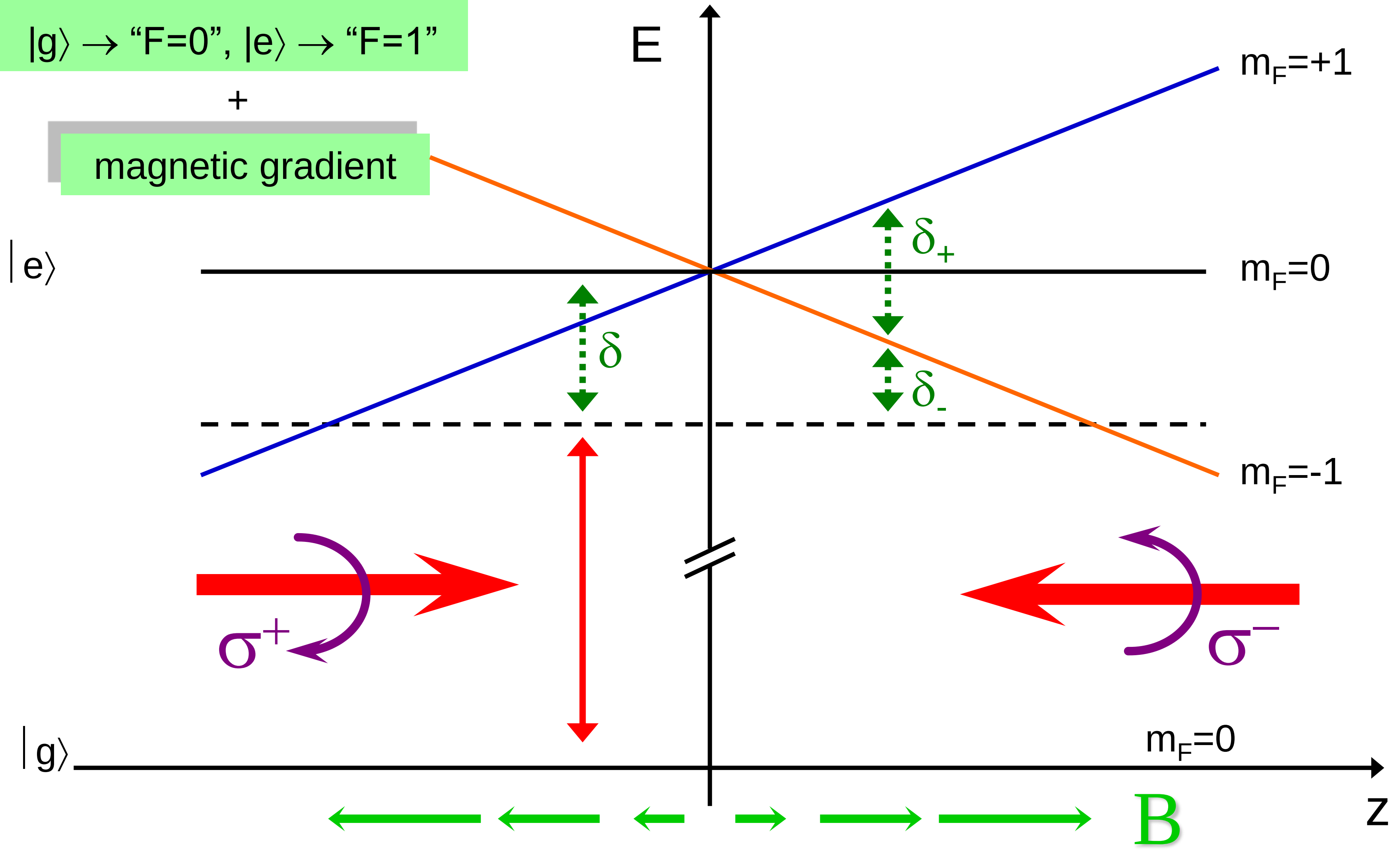

Magneto-Optical Trap

4-level atom

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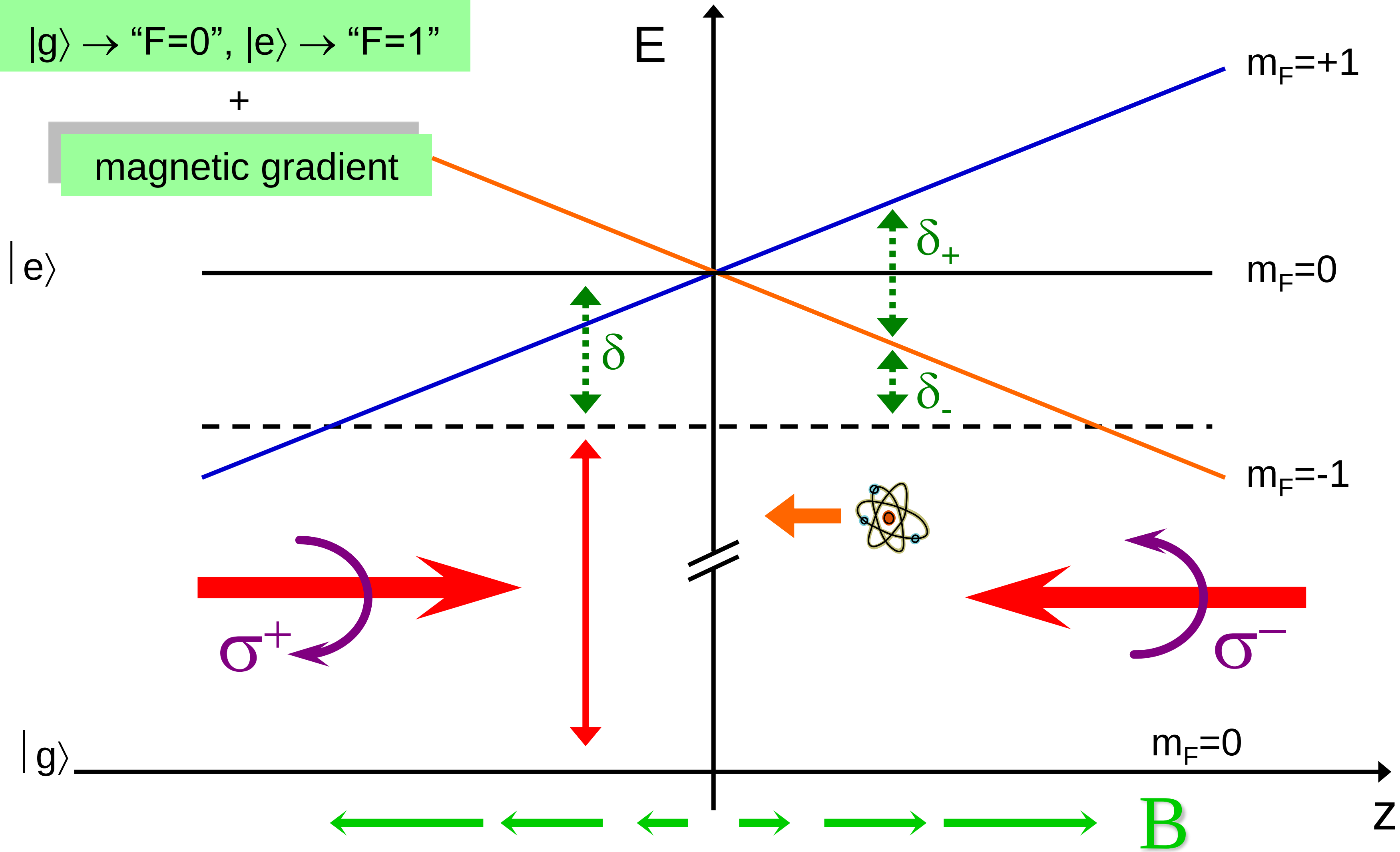
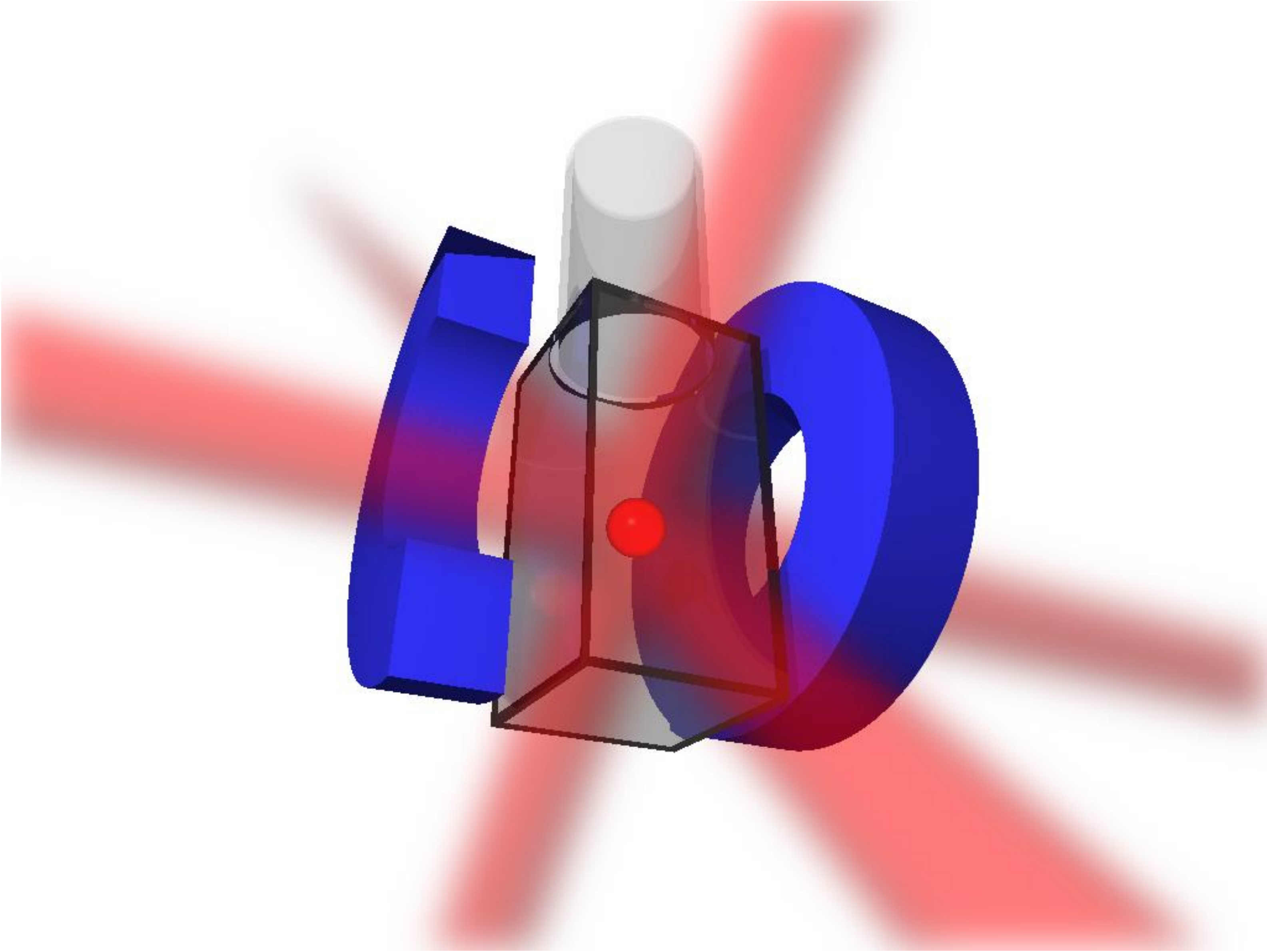
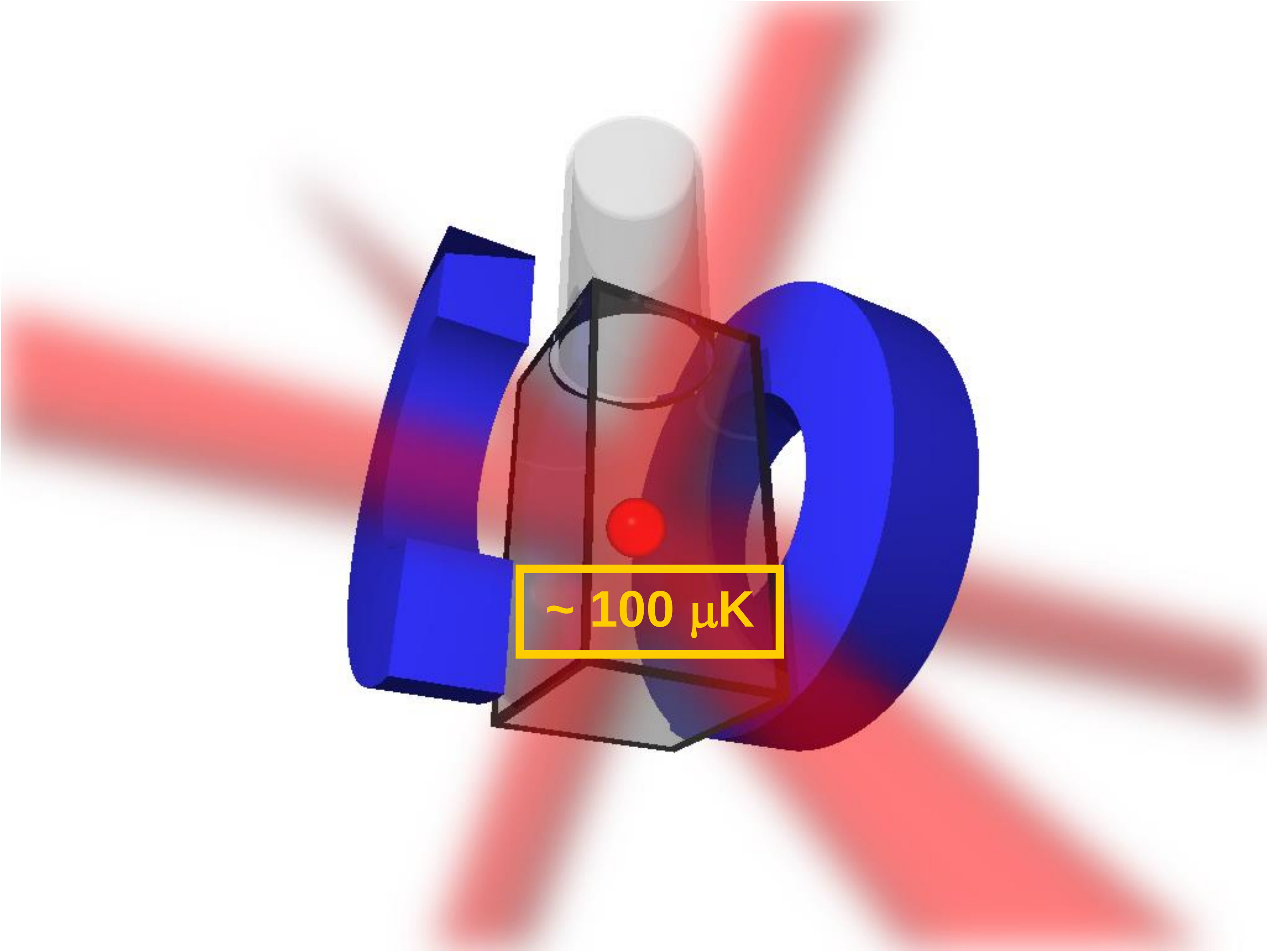


Magneto-Optical Trap (MOT)

Magneto-Optical Trap (MOT)



Magneto-Optical Trap (MOT)



Magneto-Optical Trap (MOT)

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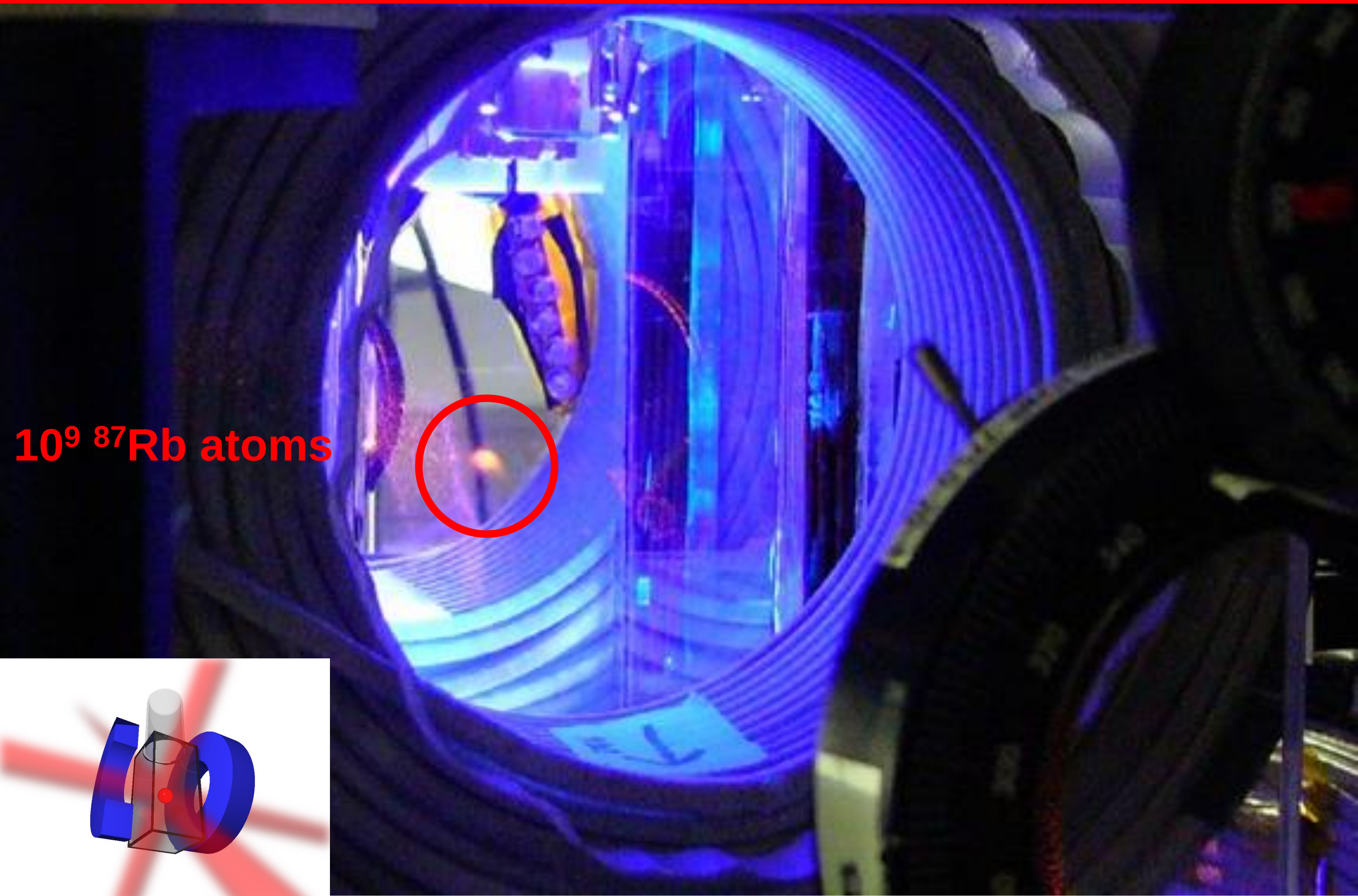


Trapping of Neutral Sodium Atoms with Radiation Pressure

E. L. Raab,[a] M. Prentiss, Alex Cable, Steven Chu,[b] and D. E. Pritchard[a]
AT&T Bell Laboratories, Holmdel, New Jersey 07733
(Received 16 July 1987)

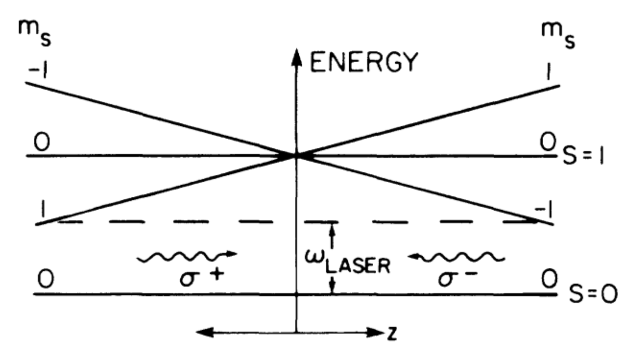
We report the confinement and cooling of an optically dense cloud of neutral sodium atoms by radiation pressure. The trapping and damping forces were provided by three retroreflected laser beams propagating along orthogonal axes, with a weak magnetic field used to distinguish between the beams. We have trapped as many as 10^7 atoms for 2 min at densities exceeding 10^{11} atoms cm^{-3}. The trap was $\simeq$0.4 K deep and the atoms, once trapped, were cooled to less than a millikelvin and compacted into a region less than 0.5 mm in diameter.

PACS numbers: 32.80.Pj

The ability to cool and trap neutral atoms has recently been demonstrated by several groups.[1-3] Their traps utilized the intrinsic atomic magnetic dipole moment or the induced oscillating electric dipole moment to confine sodium atoms about a local-field strength extremum. We report the first optical trap which relies on near-resonant radiation pressure (also called *spontaneous* light force, in contrast to *induced* light forces[4]) to both confine and cool the atoms. The trap has an effective depth of about 0.4 K, about 10 times deeper than the deepest traps previously reported.[3] It is the first trap which exploits an atom's internal structure to induce a greater absorption probability for light moving toward the center of confinement.[4,5]

The method can also work for atoms with a more complicated hyperfine structure. In the case of the sodium $3S_{1/2}$-$3P_{3/2}$ transition, e.g., the ground states have total

(a)



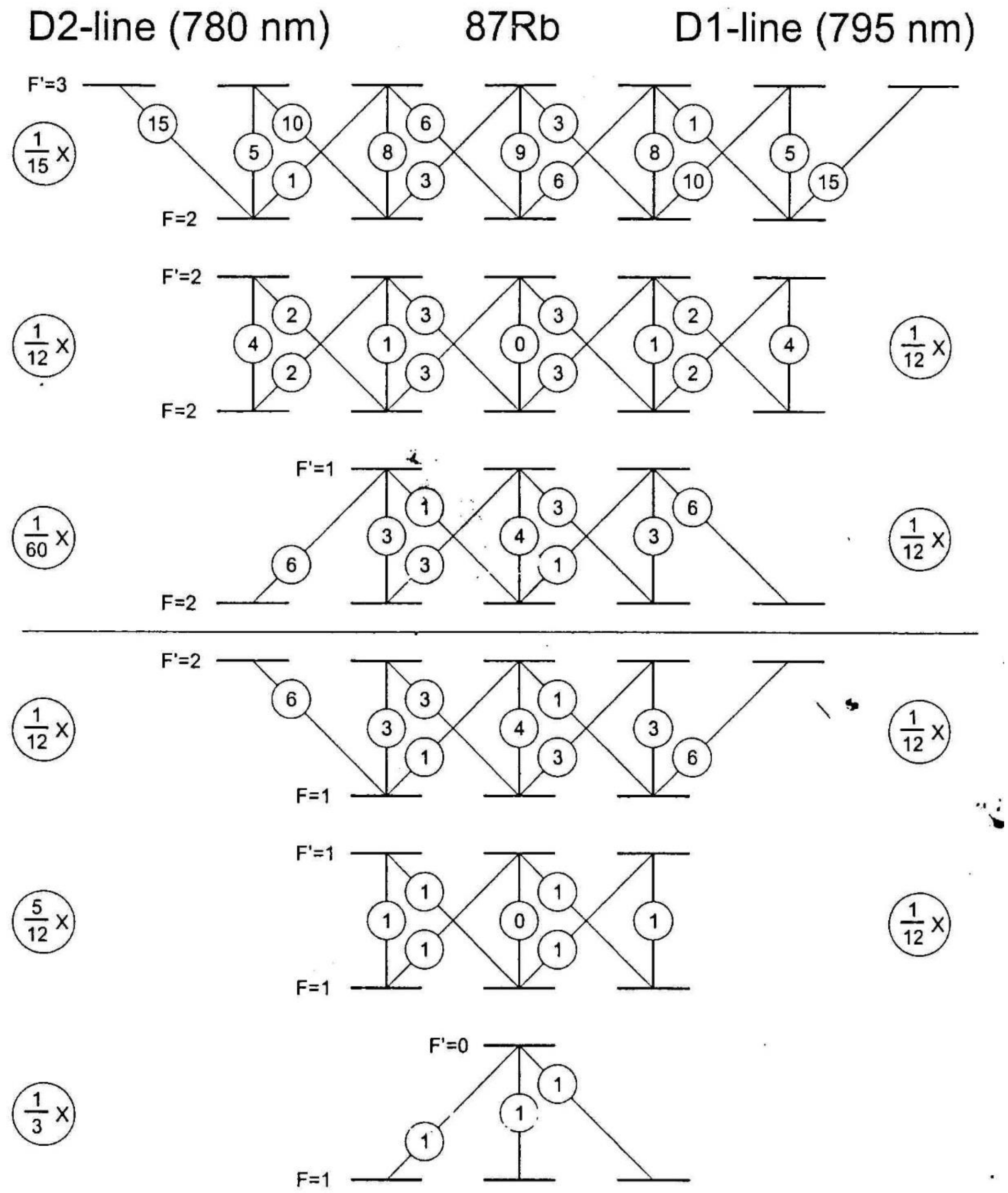
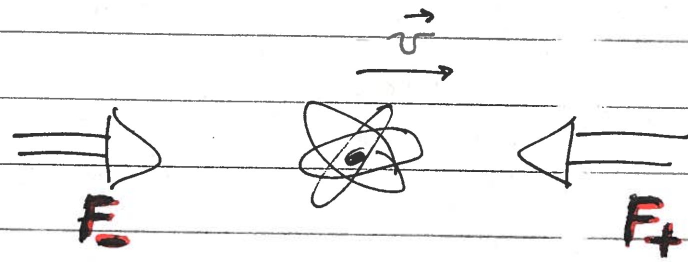


Figure A.2: Branching ratios for ^{87}Rb. Multiply by the circled number in the left(right) column to get the branching ration for the D2(D1) line.

[source: unknown PhD Thesis]

Monday, September 28, 2020

Semi-classical model of Doppler cooling



$$\vec{F} = \frac{d\vec{p}}{dt} = \text{momentum} \times \frac{\text{kicks}}{\text{sec}}$$

$$= \hbar k \, \gamma_{\text{scattering}}$$

$$= \hbar k \, \frac{s_0}{1 + s_0 + \left(\frac{2\delta}{\gamma}\right)^2} \, \frac{\gamma}{2}$$

$s_0 = \dfrac{I}{I_{sat}}$ = saturation parameter

1D model: Low intensity ($s_0 \ll 1$) so atoms do not have to "choose" between the two beams (i.e. saturation not important)

detuning: $\delta = +\delta_\ell \pm \underbrace{\omega_{\text{Doppler}}}_{\vec{k}\cdot\vec{v}} = +\delta_\ell \pm kv$

laser direction

$\delta_\ell = \omega_\ell - \omega_a$

in 1D:

$$\boxed{F_{\text{total}} = -F_+ + F_- = \frac{\hbar k \gamma s_0}{2}\left\{ \frac{-1}{1 + s_0 + \left[\frac{2(\delta_\ell + k\cdot v)}{\gamma}\right]^2} + \frac{1}{1 + s_0 + \left[\frac{2(\delta_\ell - k\cdot v)}{\gamma}\right]^2} \right.}$$

$$= \frac{\hbar k \gamma s_0}{2}\left\{ \frac{-1}{1 + s_0 + \frac{4}{\gamma^2}\left(\delta_\ell^2 + \cancel{(kv)^2} + 2kv\delta_\ell\right)} + \frac{1}{1 + s_0 + \frac{4}{\gamma^2}\left(\delta_\ell^2 + \cancel{(kv)^2} - 2kv\delta_\ell\right)} \right.$$

neglect $|kv| \ll |\delta_\ell|$ neglect low v – damping force

<u>assume:</u> $|kv| \ll \delta$

$$F \simeq \frac{\hbar k \gamma s_0}{2}\left\{\frac{-1}{1+s_0+\frac{4\delta_\ell^2}{\gamma^2}+\frac{8kv\delta_\ell}{\gamma^2}} + \frac{1}{1+s_0+\frac{4}{\gamma^2}\delta_\ell^2-\frac{8kv\delta_\ell}{\gamma^2}}\right\}$$

$$\simeq \frac{\hbar k\gamma s_0}{2}\left\{\frac{-1}{\left(1+s_0+\frac{4}{\gamma^2}\delta_\ell^2\right)\left(1+\frac{8kv\delta_\ell/\gamma^2}{1+s_0+\frac{4}{\gamma^2}\delta_\ell^2}\right)} + \frac{1}{\left(1+s_0+\frac{4}{\gamma^2}\delta_\ell^2\right)\left(1-\frac{8kv\delta_\ell/\gamma^2}{1+s_0+\frac{4}{\gamma^2}\delta_\ell^2}\right)}\right\}$$

$$\simeq \frac{\hbar k\gamma s_0}{2}\left(\frac{1}{1+s_0+\frac{4\delta_\ell^2}{\gamma^2}}\right)\left\{\cancel{-1}+\underbrace{\frac{8kv\delta_\ell/\gamma^2}{1+s_0+\frac{4}{\gamma^2}\delta_\ell^2}} + \cancel{1}+\underbrace{\frac{8kv\delta_\ell/\gamma^2}{1+s_0+\frac{4}{\gamma^2}\delta_\ell^2}}\right\}$$

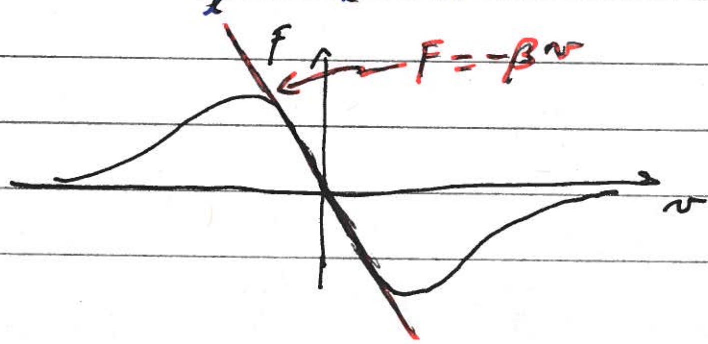
$$\simeq \frac{\hbar k\gamma s_0}{\left(1+s_0+\frac{4\delta_\ell^2}{\gamma^2}\right)^2}\,\frac{8kv\delta_\ell}{\gamma^2}$$

$$\vec{F} = \underbrace{\frac{8\hbar k^2 s_0}{\left(1+s_0+\frac{4\delta_\ell^2}{\gamma^2}\right)^2}\frac{\delta_\ell}{\gamma}}\, v \qquad \cancel{= 16\hbar k^2\gamma_{s,\text{single}}\,\delta_\ell v} \qquad \cancel{= 8\hbar k^2\gamma_{s,\text{total}}\,\delta_\ell v}$$

$-\beta v$

negative for red detuning ($\omega_\ell < \omega_a$)

$\delta_\ell = \omega_\ell - \omega_a$



Doppler Temperature

From last time:

$$\vec{F}_{cooling} = \frac{-s_0}{\left[1+s_0+\left(\frac{2\delta_L}{\gamma}\right)^2\right]^2} \frac{8\hbar k^2 \delta_L}{\gamma} v$$

The final temperature is determined by the equilibrium condition:

cooling rate = heating rate

$$\text{cooling rate} = \cancel{\text{heating rate}} \quad \frac{dE}{dt} = \text{power out}$$

$$= \vec{F}_{cooling} \cdot \vec{v}$$

for red detuning "−" in δ_L

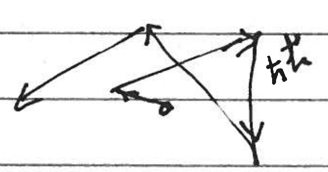
$$= \frac{+\, s_0}{\left[1+s_0+\left(\frac{2\delta_L}{\gamma}\right)^2\right]^2} \frac{8\hbar k^2 \delta_L}{\gamma} v^2$$

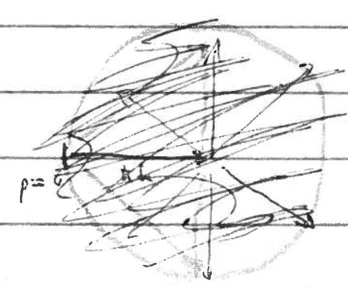
heating rate?

random direction of absorption ~~and~~ (3D) and random fluorescence scattering generates a random walk in momentum space with a step $\vec{p} = \hbar \vec{k}$

(and real space)

absorption + re-emission in 3D





$$\text{heating rate} = \frac{d}{dt}\langle E_{\text{kinetic}}\rangle$$

$$= \frac{d}{dt}\left(\left\langle \frac{p^2(t)}{2m}\right\rangle\right)$$

$$= \frac{1}{2m}\frac{d}{dt}\left\langle \vec{P}_1^{\,2} + \vec{P}_2^{\,2} + \cdots + 2\vec{P}_1\cdot\vec{P}_2 + 2\vec{P}_2\cdot\vec{P}_3 + \cdots \right\rangle$$

$$= \frac{1}{2m}\frac{d}{dt}\langle \vec{P}_1^{\,2}\rangle + \langle \vec{P}_2^{\,2}\rangle + \cdots \underbrace{2\langle \cancel{\vec{P}_1\cdot\vec{P}_2}\rangle_{\to 0} + 2\langle\cancel{\vec{P}_2\cdot\vec{P}_3}\rangle_{\to 0}}_{\text{no correlation between different scattering events}} + \cdots$$

$$= \frac{1}{2m}\underbrace{\frac{d}{dt}N(t)}_{2\times\gamma_{\text{scattering}}}(\hbar k)^2$$

$1+1$ = absorption + spontaneous absorption

$$\Rightarrow \quad \text{heating rate} = \frac{1}{2m}\,2(\hbar k)^2\,\underbrace{\gamma_{\text{scattering}}}_{2\,\frac{s_0\,\gamma/2}{1+s_0+\left(\frac{2\delta_\ell}{\gamma}\right)^2}}$$

for $\langle v\rangle = 0$
$(\langle v^2\rangle \neq 0)$

2 lasers beams counterpropagating

At equilibrium:

heating rate = cooling rate

$$\frac{2\hbar(\hbar k)^{\cancel{2}}}{2m}\;\frac{\cancel{s_0}\,\gamma}{1+s_0\cancel{+\left(\frac{2\delta_\ell}{\gamma}\right)^2}} = \frac{\cancel{s_0}}{\left[1+s_0+\left(\frac{2\delta_\ell}{\gamma}\right)^2\right]^{\cancel{2}}}\;\frac{8\cancel{\hbar k^2}\,\delta_\ell\, v}{\gamma}$$

$$\frac{2\hbar\gamma}{2m} = \frac{8\,\delta_\ell\,v^2}{\gamma\left[1+\cancel{A_0}+\left(\frac{2\delta_\ell}{\gamma}\right)^2\right]}$$

~ 0 for low intensity limit

$$\underbrace{\frac{\hbar\gamma}{2\cdot 8}\,\frac{\gamma}{\delta_\ell}\left(1+\left(\frac{2\delta_\ell}{\gamma}\right)^2\right)}_{\text{this function has a minimum for } \boxed{\delta_\ell = -\gamma/2}} = \frac{1}{2}mv^2 = \langle E_{kinetic}\rangle$$

$$\frac{\hbar\gamma}{\cancel{16}8}\,\frac{\cancel{\gamma}}{\cancel{\gamma/2}}\left(1+\left(\frac{\cancel{2}\,\cancel{\gamma/2}}{\cancel{\gamma}}\right)^2\right) = \langle E_{kinetic}\rangle$$

$$\Leftrightarrow \quad \frac{\hbar\gamma}{4} = \frac{1}{2}k_B T$$

$$\Rightarrow \quad T = \frac{\hbar\gamma}{2k} = \text{Doppler cooling limit}$$

or

Doppler Temperature

$T \triangleq 180\,\mu K$ for ^{87}Rb

$\hbar = 1.054 \times 10^{-34}$

$\gamma = 2\pi \times 6\,MHz$

$k = 1.38 \times 10^{-23}\,J/K$