Laser Cooling And Trapping

Quantum Optics 2008

Gal Aviv

Outline

- *How to Define Temperature*
- *Forces on two-Level Atoms*
- *Two-Level Atom at Rest*
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  - *Zeeman Splitting*
- *Deceleration of an Atomic Beam*
- *Optical Molasses*
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- *Magnetic Traps*
- *MOT*
- *Bose-Einstein Condensation*
- *Dipole Force*
- *Optical Lattices*

How to Define Temperature

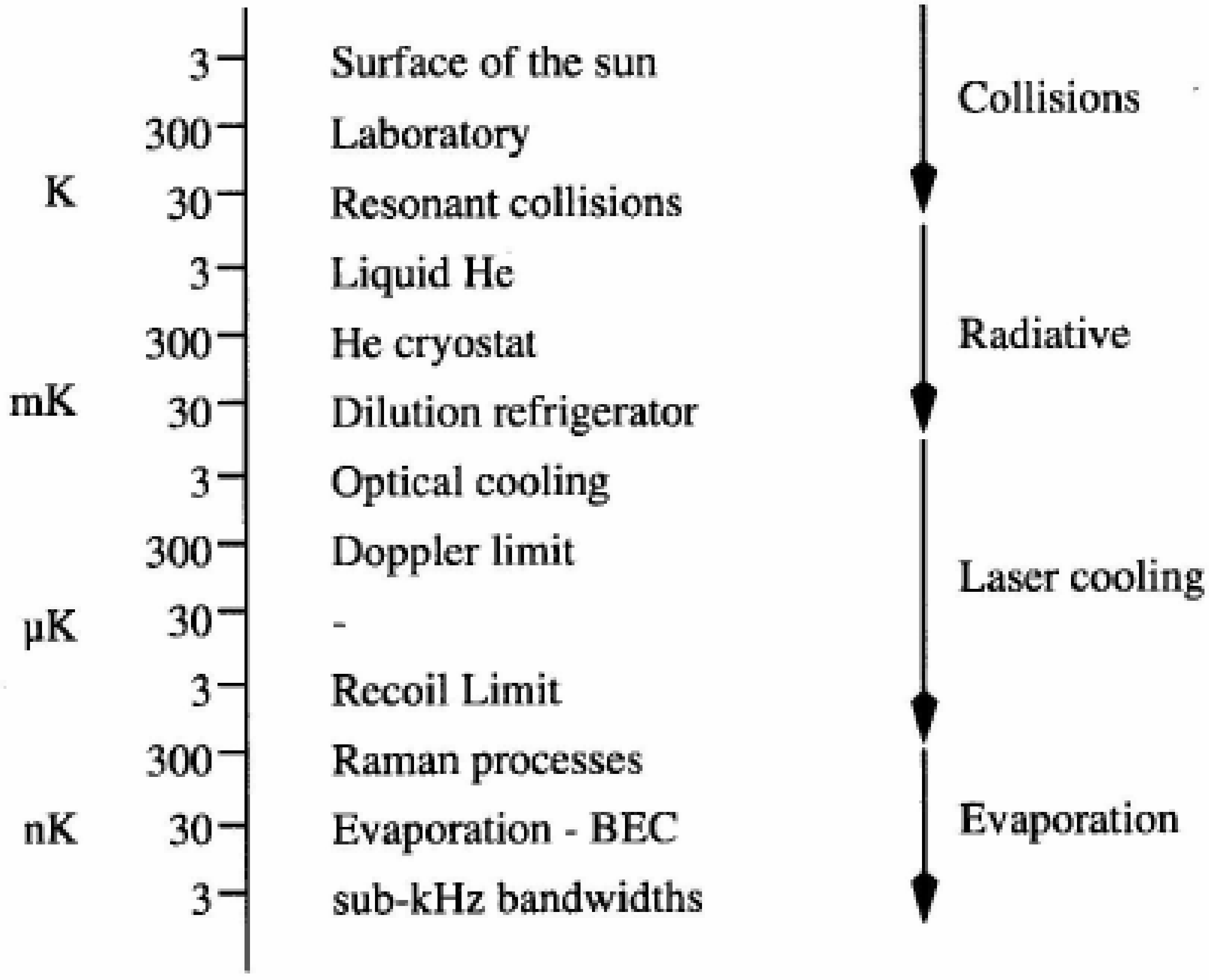


FIGURE 5.1. Temperature scale.

How to Define Temperature

- From Maxwell-Boltzmann eq.:

$$\frac{1}{2}k_B T = < E_k >$$

$$v_c \equiv \gamma / k \approx 1_{m/s}$$

- Boundary of absorption of light:

$$k_B T_C = \frac{M\gamma^2}{k^2}$$

- Doppler temperature:

$$k_B T_D \equiv \frac{\hbar\gamma}{2}$$

$$v_D = \sqrt{k_B T_D / M} \approx 30_{cm/s}$$

- Recoil limit:

$$v_r = \hbar k / M \approx 1_{cm/s}$$

$$k_B T_D \equiv \frac{\hbar k^2}{M}$$

Forces on two-Level Atoms

- The semi classical description:
  - Ehrenfest theorem:

    Laser light Pressure

- Quantum Mechanic form:

(using the electric dipole approximation, in the last part, which allows to interchange the gradient and the expected value)

$$\langle A \rangle = Tr(\rho A)$$

$$F = \langle f \rangle = \frac{d}{dt}\langle p \rangle$$

$$\frac{d}{dt}\langle A \rangle = \frac{i}{\hbar}\langle [H, A] \rangle$$

$$\langle [H, p] \rangle = \frac{i}{\hbar}\frac{\partial H}{\partial z}, \; p = -i\hbar(\partial / \partial z)$$

$$F = -\left\langle \frac{\partial H}{\partial z} \right\rangle$$

$$\langle f \rangle = F = e\left\langle \frac{\partial}{\partial z}\left(\vec{\mathrm{E}}(\vec{r}, t) \cdot \vec{r}\right) \right\rangle$$

$$F = e\frac{\partial}{\partial z}\left\langle \left(\vec{\mathrm{E}}(\vec{r}, t) \cdot \vec{r}\right) \right\rangle$$

General Solution for the force:

$$F = \hbar\left(\frac{\partial \Omega}{\partial z}\rho_{eg}^{*}\rho_{eg}^{*} + \frac{\partial \Omega^{*}}{\partial z}\rho_{eg}\right)$$

$$\frac{\partial \Omega}{\partial z} = (q_r + iq_i)\Omega$$

$$F = \hbar q_r\left(\Omega\rho_{eg}^{*} + \Omega^{*}\rho_{eg}\right) + i\hbar q_i\left(\Omega\rho_{eg}^{*} + \Omega^{*}\rho_{eg}\right)$$

A Two-Level Atom at Rest

- Electric field of Standing wave:

$$E(z) = E_0 \cos(kz)\left(e^{-iwt} + c.c.\right)$$

- The force from spontaneous emission:

$$F_{sp} = \hbar k \gamma \rho_{ee}$$

  k- momentum transfer from each photon.
  γ- the rate of the process.
  ρ-probability for atom to be in a state.

- Absorption force (Radiation):

$$F_{sp} = \frac{\hbar k s_0 \gamma / 2}{1 + s_0 + (2\delta / \gamma)^2}$$

  - Atom that absorb a photon releases it in spontaneous emission thaw gain momentum.
  - The force direction is in the light direction.
  - The force saturates at large intensity.
  - $S_0=I/I_0$ –saturation parameter of a beam that forms standing wave.
  - γ- decay rate
  - δ -detuning

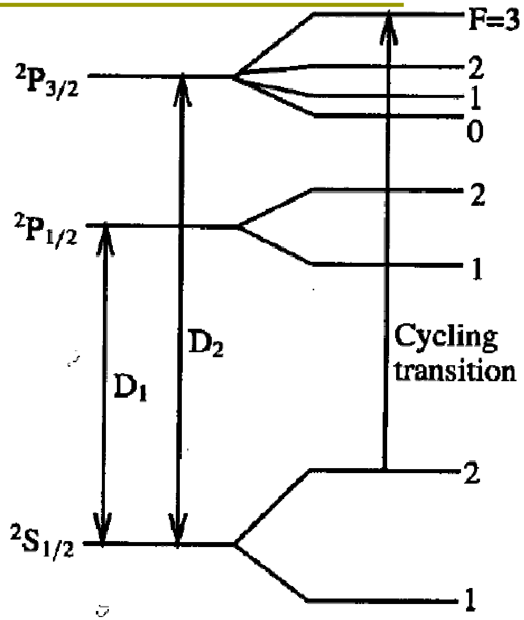
A Two-Level Atom at Rest

- Dipole Force (for standing wave):

$$F_{dip} = \frac{2\hbar k \delta s_0 \sin(2kz)}{1 + 4s_0 \cos^2(kz) + (2\delta/\gamma)^2}$$

Multilevel Atoms

- Alkali-Metal Atoms:
  - First to be cooled and trapped.
  - Excitation frequency in visible light.
  - Large vapor pressure at a modest temperature.
  - Easy to generate an atomic beam.
  - Have a closed shell with one valence electron.



- Fine Structure:

$$|l-s| \le j \le l+s$$

$$l - \text{orbital angular momentum}$$

$$s - \text{spin angular momentum}$$

$$j - \text{total angular momentum}$$

- Hyper-Fine Structure:

$$|I-J| \le F \le I+J$$

$$I - \text{nuclear spin}$$

$$F - \text{total angular momentum}$$

Zeeman Splitting

- These dependencies lifts by
  external magnetic filed B.
- (2I+1)x(2J+1) sublevels.
  - M- projection of the angular momentum along B.
  - g- Lande g-factor.
  - L,S,J – Refer to the electron's angular momentum.

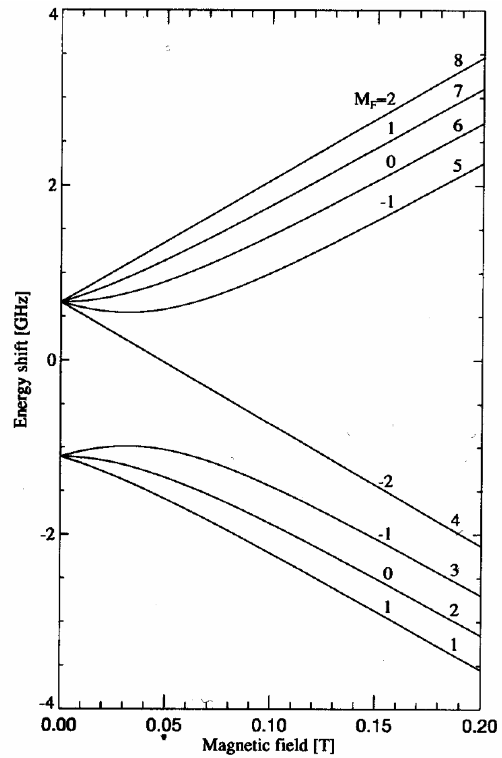


FIGURE 4.2. Energies of the ground hyperfine states of Na, where the states are numbered 1–8 and M_F is the projection of the total angular momentum of the atom on the magnetic field axis.

$$\Delta E = g\mu_B MB$$

$$\mu_B \equiv e\hbar / 2m_e c$$

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

$$g_F = g_J \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)}$$

Deceleration of an Atomic Beam

- Doppler effects:
  - Rate: $\gamma_p = \dfrac{s_0\gamma/2}{1+s_0+[2(\delta+w_D)/\gamma]^2}$
  - Force: $\vec{F} = \hbar\vec{k}\gamma_p$
  - Stopping length: $L_{\min} = \bar{v}^2/2a_{\max}$
  - Stopping time: $t_{\min} = \bar{v}/a_{\max}$
  - Saturation deceleration: $\vec{a}_{\max} = \hbar\vec{k}\gamma/2M$
  - Necessary condition $(\delta + w_D) << \gamma$
  - Doppler force applet
  - repeat cycles

atom	T_{oven} (K)	$\bar{v}$ (m/s)	$L_{\min}$ (m)	$t_{\min}$ (ms)
H	1000	5000	0.012	0.005
He*	4	158	0.03	0.34
He*	650	2013	4.4	4.4
Li	1017	2051	1.15	1.12
Na	712	876	0.42	0.96
K	617	626	0.77	2.45
Rb	568	402	0.75	3.72
Cs	544	319	0.93	5.82

TABLE 6.1. Parameters of interest for slowing various atoms. The stopping length $L_{\min}$ and time $t_{\min}$ are minimum values. The oven temperature T_{oven} that determines the peak velocity is chosen to give a vapor pressure of 1 Torr. Special cases are H at 1000 K and He in the metastable triplet state, for which two rows are shown: one for a 4 K source and another for the typical discharge temperature.

Deceleration of an Atomic Beam

- Laser Frequency sweep:
  - Laser frequency sweep upward to compensate the deceasing Doppler shift at the atoms slow down.
  - Easy to use with semiconductor laser diodes.
  - Slow atoms arrive in pulses.
- Broad Band light:
  - Wide spectral range light.
  - Demands 100 times the intensity.
- Diffuse light:
  - Atoms moving through diffuse monochromatic light see a range of frequencies that vary with the angel between velocity and light direction. $w_D = -\vec{k}\cdot\vec{v}, \delta = w_l - w_a = kv\cos\theta = -w_D$
- DC Stark shift.
- Changing the magnetic field.

$$E_{(z)} = E_0\sqrt{1-\sqrt{1-z/z_0}}$$

$$B_{(z)} = B_0\sqrt{1-z/z_0}$$

Changing the magnetic field (1D)

$$B_{(z)} = B_0\sqrt{1 - z/z_0}$$

$$z_0 = mv_0^2/\eta\hbar k\gamma$$

$$B_0 = \hbar k v_0/\mu', \mu' \equiv (g_e M_e - g_g M_g)\mu_B$$

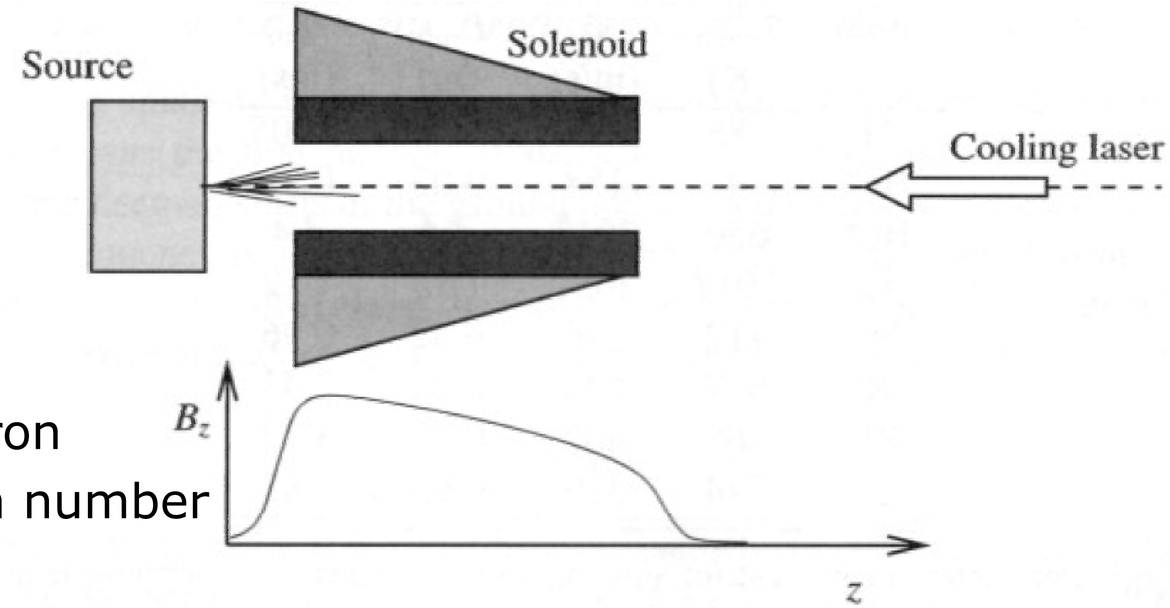


FIGURE 6.1. Schematic diagram of apparatus for beam slowing. The tapered magnetic field is produced by layers of varying length on the solenoid. A plot of B_z *vs.* z is also shown.

g- Land'e g-factor
\mu_B Bohr magnetron
M-magnetic quantum number
γ- decay rate

Zeeman-tuning technique

- H. Metcalf *et-al. phys. Rev. A* ***55***, 605-614 (1997)
- TOF technique.
- Na atoms pass throw aperture of 1mm^2.
- The source heated up to 300^{0}C.
- Initial speed 1000 m/s and spread of 0.01 radians
- Final speed 50 m/s and spread 0.2 radians

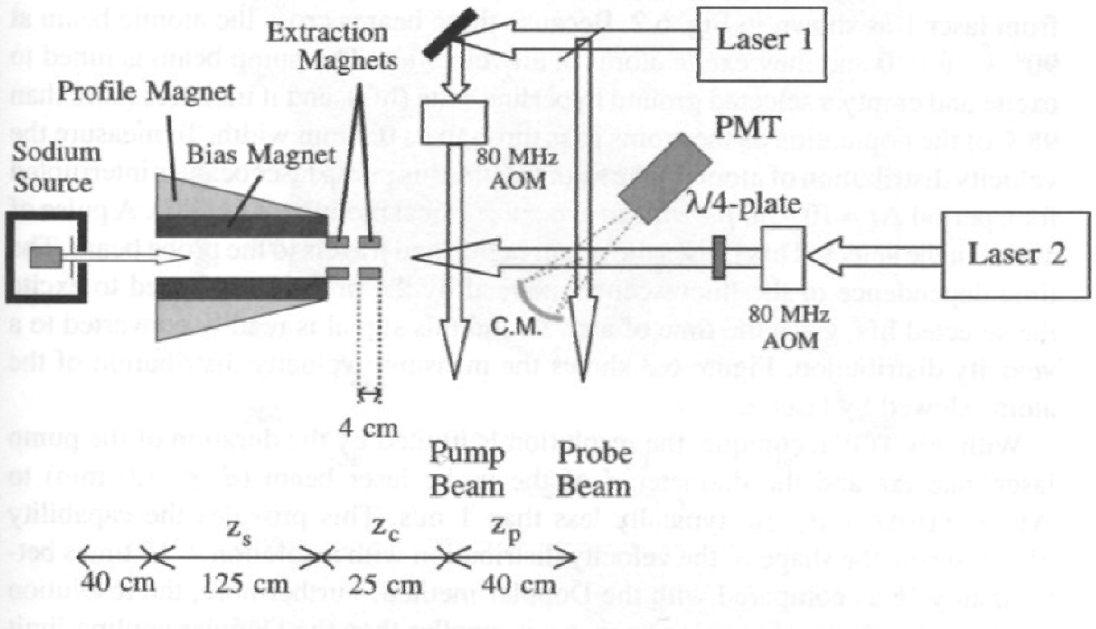


FIGURE 6.2. The TOF apparatus, showing the solenoid magnet and the location of the two laser beams used as the pump and probe. The resolution of the technique is ultimately determined by the flight path z_p (figure from Ref. 65).

Measurements and Results

- The pump and probe are perpendicular to the beam therefore excites all velocities.
- The pump excites 98% of the atoms to selected hfs.
- The pump width is 0.5mm.
- The pump interrupted for period $\Delta t=10\text{-}50\mu s$ with AOM.
- Resolution of 1m/s

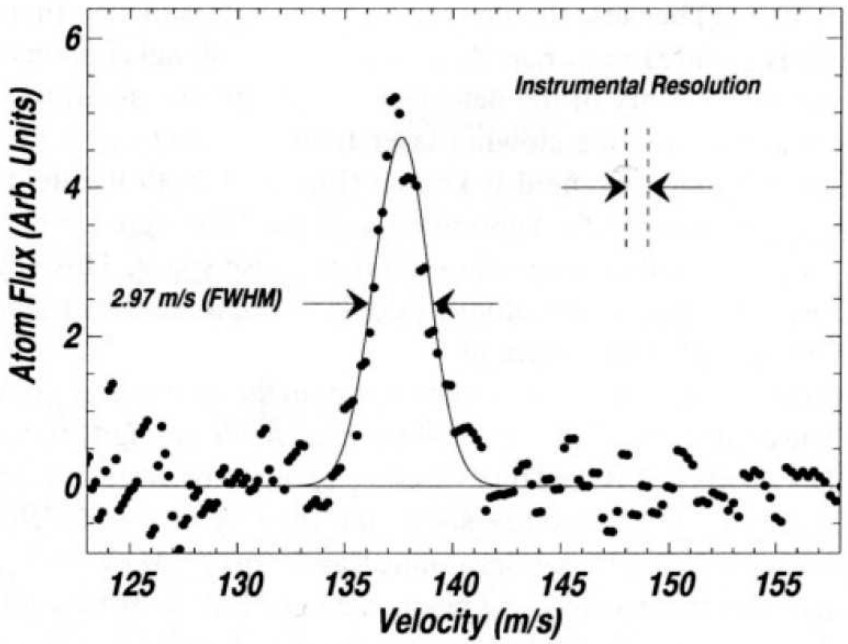


FIGURE 6.3. The velocity distribution measured with the TOF method. The experimental width of approximately $\frac{1}{6}(\gamma/k)$ is shown by the dashed vertical lines between the arrows. The Gaussian fit through the data yields a FWHM of 2.97 m/s (figure from Ref. 65).

Measurements and Results

- Cooling Suring Deceleration:
  - Deceleration is *not* the same as cooling.
  - Cooling: compression of the velocity in the phase space.
  - All atoms with velocity below v_0 are swept into a narrow velocity group around the final velocity.
- Shutting off the slowing laser beam:
  - Shut off the slowing beam τ_{off} before short shut-off of the pump beam.
  - Gives 2D graphs of the atoms in the solenoid.
- Optical pumping during deceleration:
  - The cooling beam pump the atoms to the HFS levels.
  - Many absorption and emissions are required to have a significant effect on the atom velocity.
  - The laser beam's polarization operates on a cycling transition that conect the states: $F_g=2, M_g=2$ *with* $F_e=3, M_e=3$.

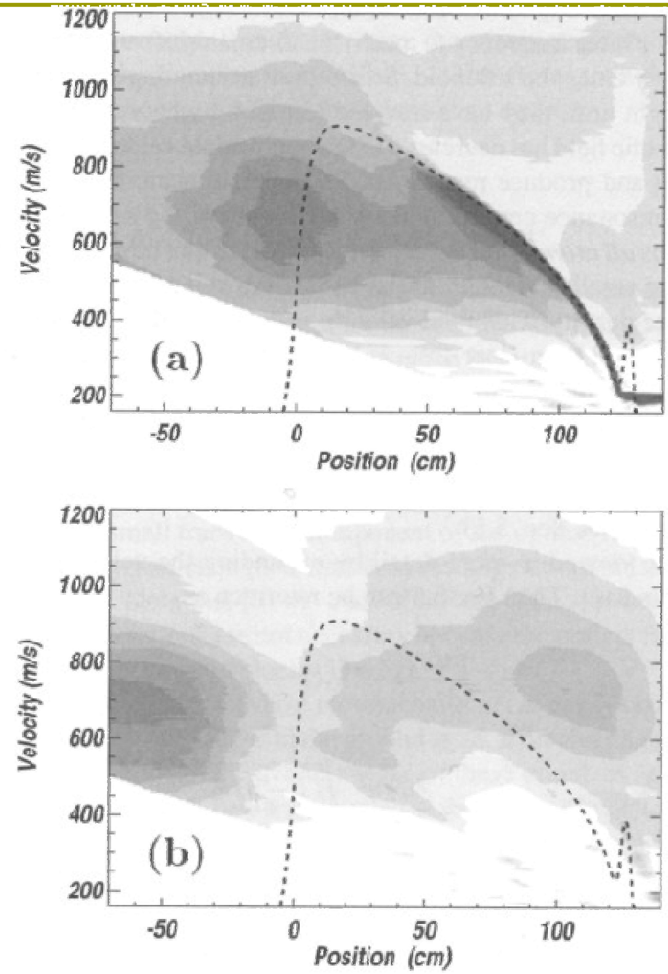


FIGURE 6.4. Contour map of the measured velocity and position of atoms in the solenoid, (a) for $F_g = 2$ atoms and (b) for $F_g = 1$ atoms. The dashed line indicates the resonance frequency for the $(F, M_F) = (2, 2) \rightarrow (3, 3)$ cycling transition. The density of atoms per unit phase space area $\Delta v \Delta z$ has been indicated with different gray levels (figure from Ref. 65).

Optical Molasses

- No a trap for neutral atoms because there is no restoring force.
- Viscous damping.
- Using red detune Laser.
- Keeping the frequency, intensity, polarization and phase on each line by use of mirrors.
- Optical molasses applet

- Low-Intensity Theory for 2-level atom in 1D.

$$\vec{F}_{OM} = \vec{F}_{+} + \vec{F}_{-}$$

$$\vec{F}_{OM} = \pm \frac{\hbar \vec{k} \gamma}{2} \frac{s_0}{1 + s_0 + \left[2(\delta \mp |w_D|)/\gamma\right]^2}$$

$$\vec{F}_{OM} \cong \frac{8\hbar k^2 \delta s_0 \vec{v}}{\gamma(1 + s_0 + (2\delta/\gamma)^2)^2} \equiv -\beta \vec{v}$$

$$s_0 \leq 1, |v| = \gamma / k$$

$$v_{capture} = \gamma / k$$

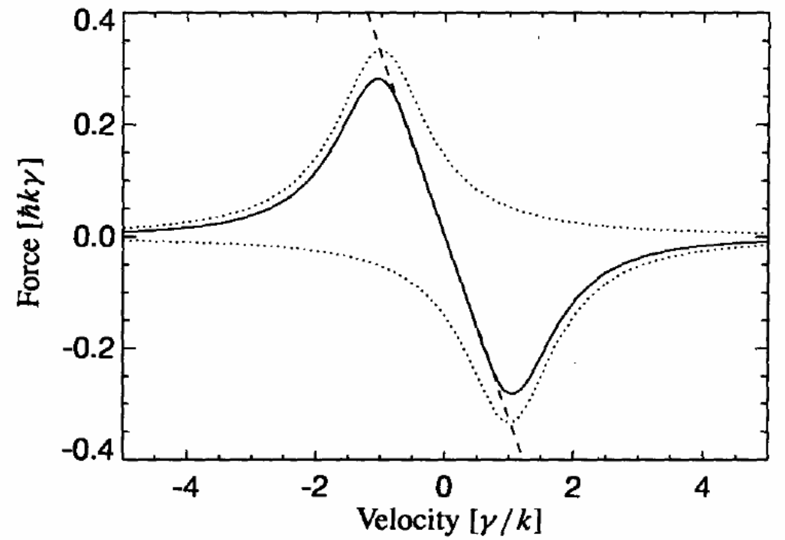


FIGURE 7.1. Velocity dependence of the optical damping forces for one-dimensional optical molasses. The two dotted traces show the force from each beam, and the solid curve is their sum. The straight line shows how this force mimics a pure damping force over a restricted velocity range. These are calculated for $s_0 = 2$ and $\delta = -\gamma$ so there is some power broadening evident (see Sec. 2.4).

Is T reaches 0?

- v=0, T=0 seems un physical result.
- Heating caused by laser beam:
  - Recoil energy:
  - Average frequency for each absorption:
  - Average frequency for each emission:
  - Energy that the light loss for each scattering:
  - The loss rate:
  - The emission is in random direction.
  - The sample being heat up.
- This is the Doppler limit
  - The steady state kinetic energy:
  - The minimum is where:
  - And the Doppler temperature is:
- Note that the average momentum transfer is zero, but the rms finite.

$$E_r = \hbar^2 k^2 / 2M = \hbar w_r$$

$$w_{abs} = w_a + w_r$$

$$w_{emit} = w_a - w_r$$

$$\hbar(w_{abs} - w_{emit}) = 2\hbar w_r$$

$$2\gamma_p$$

$$E_{k-steady\_state} = (\hbar\gamma/8)(2|\delta|/\gamma + \gamma/2|\delta|)$$

$$E_{k-\min} \rightarrow \delta = -\gamma/2$$

$$T_D = \hbar\gamma/2k_B < 1mK$$

Atomic Beam Collimation -1D

- A way to increase the brightness of an atomic beam.
- Using OM to restrict the atoms motion for certain direction.
- V_0=500m/s, aperture~330μm diameter.

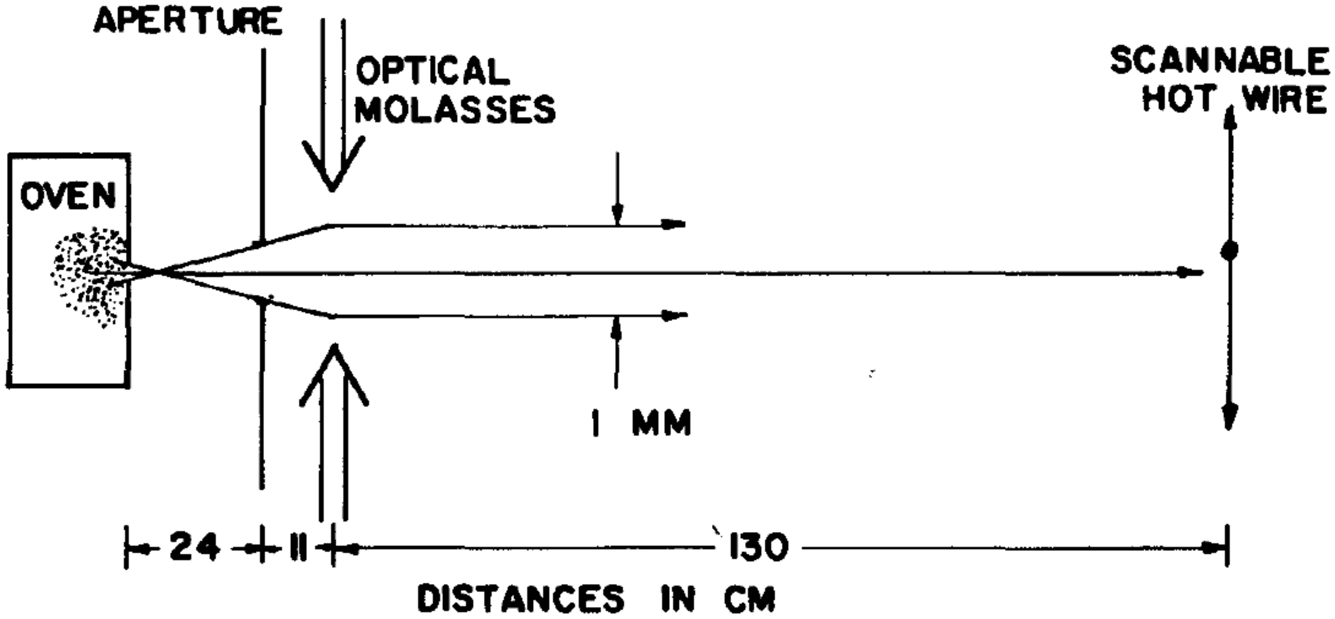


FIGURE 7.2. Overall schematic of the apparatus used for one-dimensional transverse cooling (figure from Ref. 76).

Atomic Beam Collimation -2D

- Creates atomic beams 10^6 or more times intense then ordinary thermal beam.
- Rb atoms T~150^{0}C.

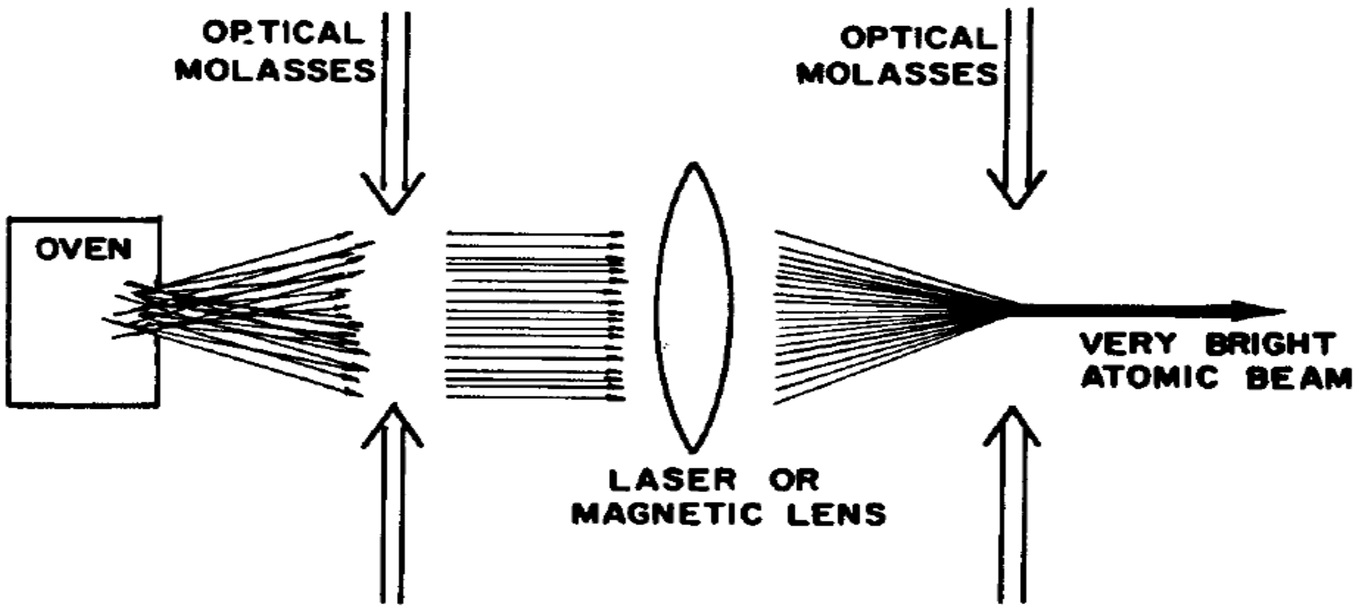


FIGURE 7.3. Scheme for optical brightening of an atomic beam. First the transverse velocity components of the atoms are damped out by an optical molasses, then the atoms are focused to a spot, and finally the atoms are recollimated in a second optical molasses (figure from Ref. 76).

Early 2D collimation experiment

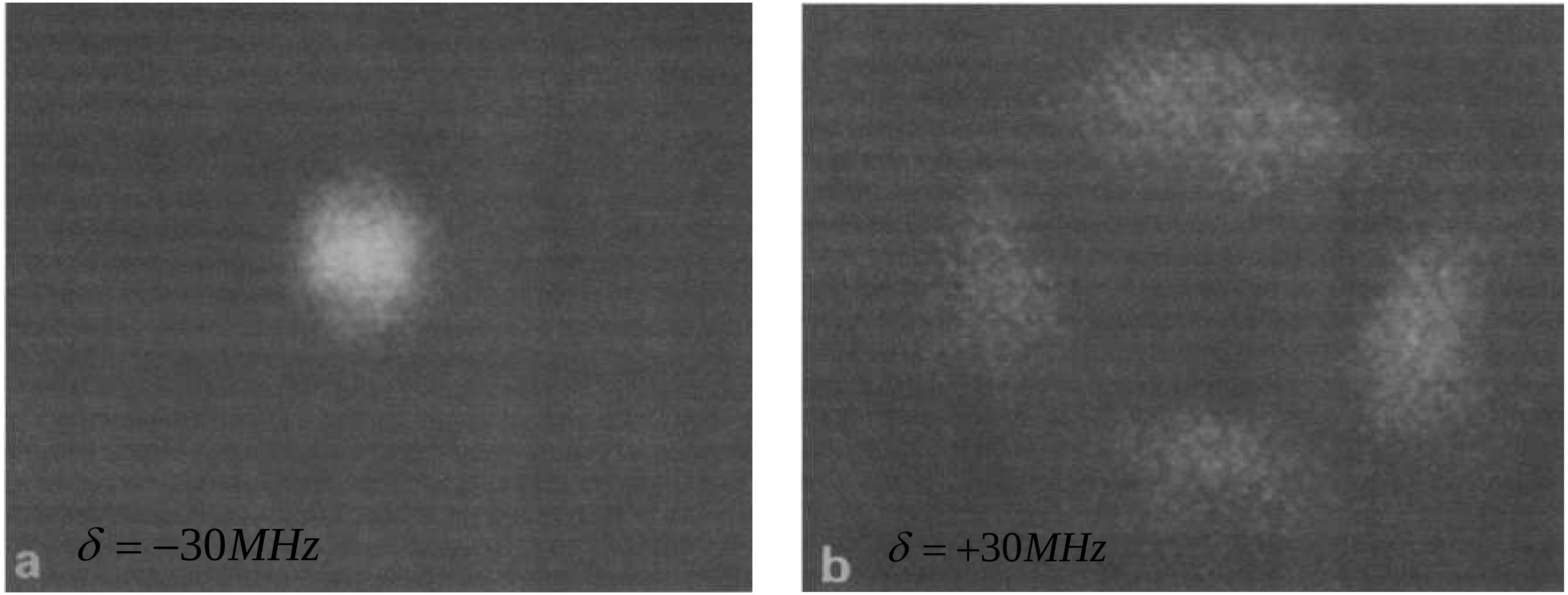


FIGURE 7.5. Image formed by the neutral atom camera of Fig. 7.4 with two-dimensional molasses acting on the atomic beam. The outline of the circular beam spot represents a 6 mm diameter image on the phosphor. The 7 mW molasses laser beam was nearly uniformly intense and rectangular, about 8×20 mm. Its detuning was about −30 MHz for (a) and about +30 MHz for (b). Note the collimation for the red detuning and the divergence for the blue detuning. Again the recording time was $^{1}/_{30}$ s and no image averaging was performed (figure from Ref. 76).

Imaging System 2D

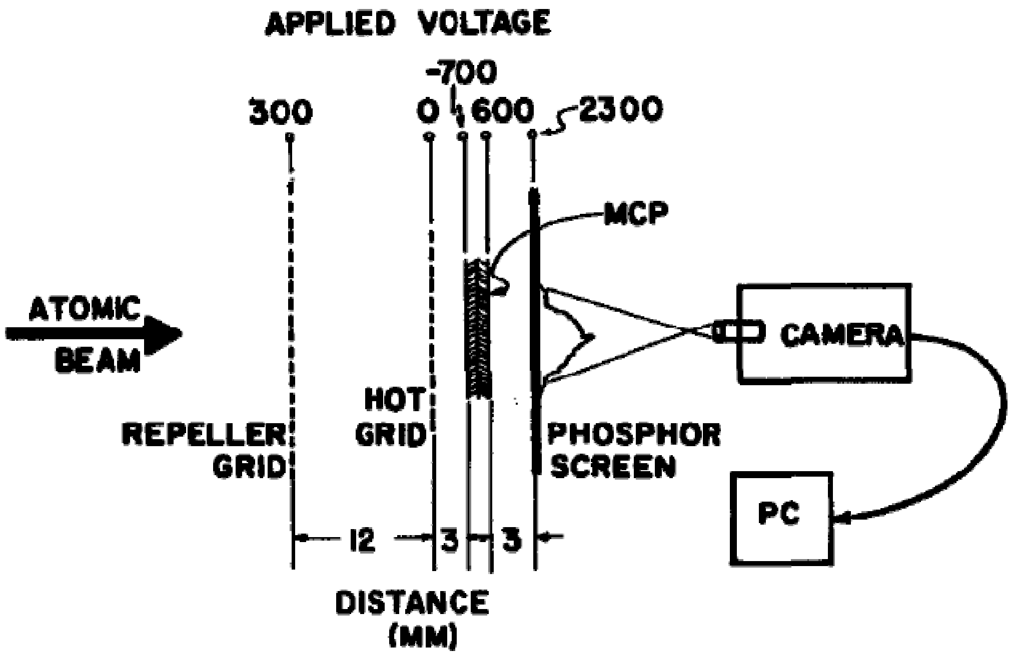


FIGURE 7.4. Schematic diagram of the neutral-atom camera showing the repeller grid, the hot grid, the multichannel plates, and the phosphor screen. Atoms are ionized at the hot grid, directed toward the MCP's by the field between it and the repeller, and accelerated toward the MCP's by the voltage between them and the hot grid. The output electrons excite the phosphor, which is viewed by the TV camera. PC is a personal computer (figure from Ref. 77).

Three-Dimensional Optical Molasses

- A. Ashkin *et-al. Phys. Rev. lett.* ***5***, 48 (1985)
- Intersection of three mutually orthogonal pairs of opposite laser beams.
- Atoms can be collected and cooled in the intersection region.
- Still *not* a trap, no return force in present.
- Atoms defuse off the region (1cm~30s).

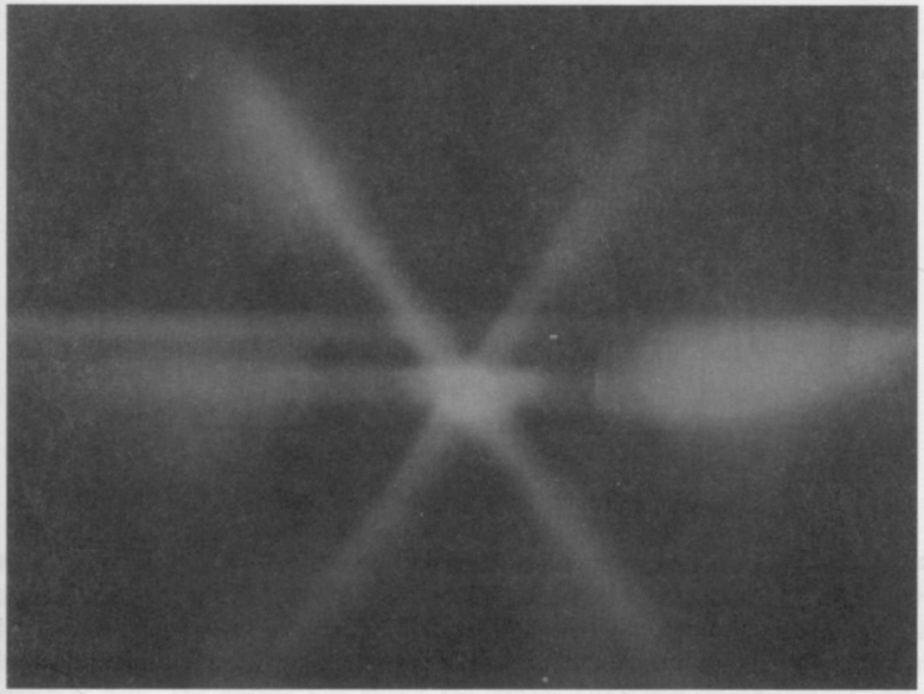


FIGURE 7.7. Photograph of optical molasses in Na taken under ordinary snapshot conditions in the lab at NIST. The upper horizontal streak is from the slowing laser while the three beams that cross at the center are on mutually orthogonal axes viewed from the (111) direction. Atoms in the optical molasses glow brightly at the center (figure from Ref. 81).

Measuring the Temperature

- The shine of the OM beam created a measuring error.
- NIST developed new technique by turning off the 3D OM and turning on 1D OM from the lower part of the cell.
- The atoms arrival time created more precise temperature measurements.

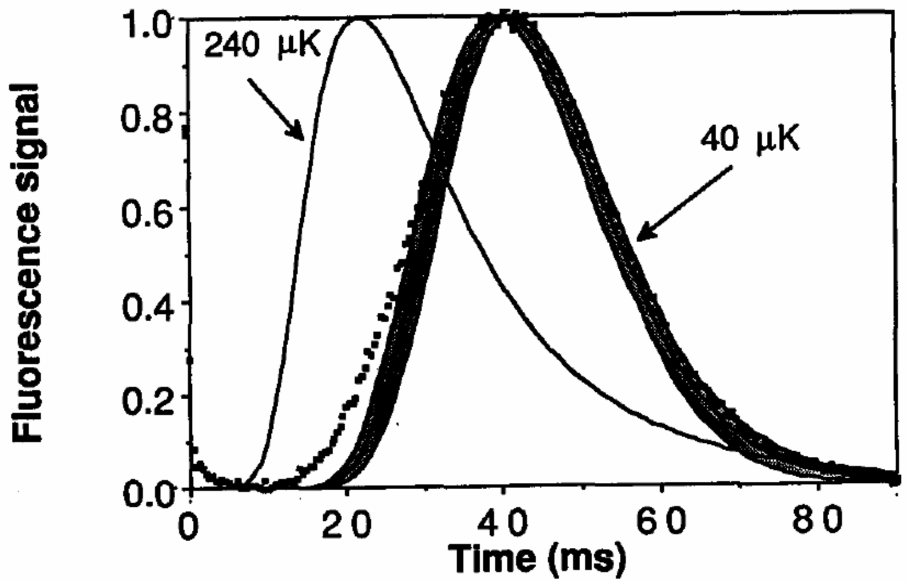


FIGURE 7.8. Data from dropping atoms out of optical molasses into a probe beam about 18 mm below. The calculated time-of-flight spectra are for 240 μK and 40 μK. The shaded area indicates the range of error in the 40 μK calculation from geometric uncertainties. The width of the data is slightly larger than the calculation, presumably because of shot-to-shot instabilities (figure from Ref. 82).

How does the Detuning effects the Temperature?

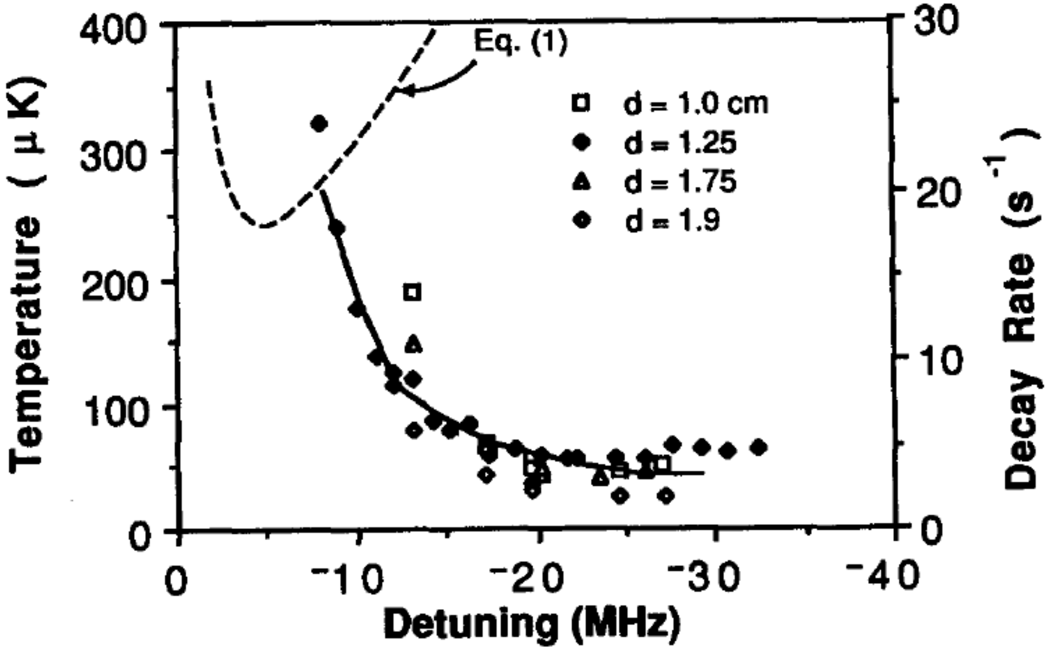


FIGURE 7.9. Temperature *vs.* detuning determined from time-of-flight data for various separations *d* between the optical molasses and the probe laser (data points). The solid curve represents the measured molasses decay rate; it is not a fit to the temperature data points, but its scale (shown at right) was chosen to emphasize its proportionality to the temperature data. The dashed line shows the temperature expected on the basis of the two-level atom theory of Sec. 7.2 (figure from Ref. 82).

Cooling Below the Doppler Limit…

- The temperature that was measured for the 3D OM was under T_D.
- Non-adiabatic response of moving atoms to the light field.
- Techniques using Laser polarization developed.

Cooling Below the Doppler Limit…

- *Dalibard and Cohen-Tannoudji. J. Opt. Soc. Am B* **6**, 2058-2071 (1989)
- *Linear $\perp$ Linear Polarization Gradient Cooling.*
  - *Light Shifts*
  - *Linear Polarization*
  - *Sub-Doppler cooling with linear light*
- *Circular Polarized light*
  - *Sub-Doppler cooling with circular polarized light*
- *Recoil Limit…*

Light Shifts

$$\Delta E_g = \frac{\hbar \delta s_0 C_{ge}^2}{1+(2\delta/\gamma)^2}$$

- Light Shift is the AC Stark shift.
- Coupling between two levels shifts their energies.
- C_{ge}- The Clebsch-Gordan coefficient that describes the coupling between the atom and light field..

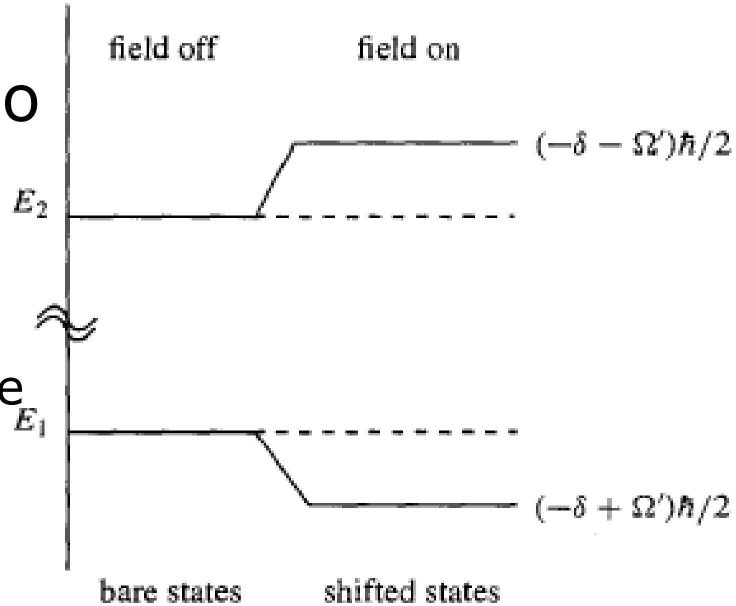


FIGURE 1.2. Energies of the two coupled states with the light field off and the light field on. The states are shifted due to the atom-light interaction, and the shift is called light shift.

Linear Polarization

- The electric field for linear polarized light:

$$\vec{E} = E_0\hat{\varepsilon}\cos(w_l t - kz) + E_0\hat{\varepsilon}\cos(w_l t + kz) =$$
$$= 2E_0\hat{\varepsilon}\cos(kz)\cos(w_l t)$$

- For two counter propagating laser beams both linear:

$$\vec{E} = E_0\hat{x}\cos(w_l t - kz) + E_0\hat{y}\cos(w_l t + kz) =$$
$$= E_0\left[(\hat{x}+\hat{y})\cos(kz)\cos(w_l t) + (\hat{x}-\hat{y})\sin(kz)\sin(w_l t)\right]$$

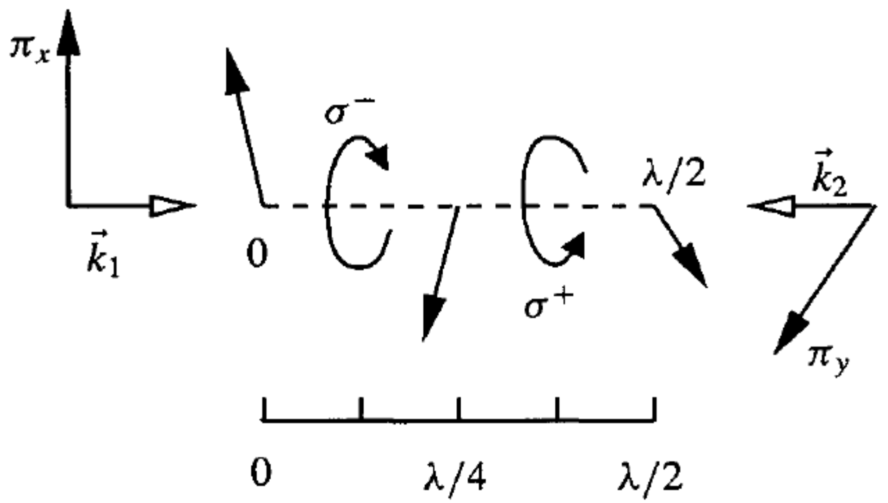
- At the origin:

$$\vec{E} = E_0(\hat{x}+\hat{y})\cos(w_l t)$$

- At $z=\lambda/8$, where $kz=\pi/4$:

$$\vec{E} = E_0\left[\hat{x}\sin(w_l t + \pi/4) - \hat{y}\cos(w_l t + \pi/4)\right]$$

- **At z=λ/8 and at *z=3λ/8* where *kz=3π/4; E represent circular polarized light at opposite directions.***
- **There is strong polarization gradient.**
- **Sisyphus Cooling**



.5. Polarization gradient field for the lin ⊥ lin configuration (see also Chapter 8).

Sub-Doppler cooling with linear light

- The Stark Shift for two level atom in traveling wave:
- Two traveling waves- Light shift twice large.
- The coupling has been modified because of the multiplicity of the ground-state, C_{ge}.
- A C_{ge} depends on the magnetic quantum number and on the polarization of light field.
- For σ^+ light $M_g=1/2$ three times larger them $M_g=-1/2$.
- For σ^- light the opposite.

$$\Delta E_{g(traveling)} = \frac{\hbar\Omega^2}{4\delta}$$

$$\Delta E_{g(2-traveling)} = \frac{\hbar\delta s_0 C_{ge}^2}{1+(2\delta/\gamma)^2}$$

Sub-Doppler cooling with linear light

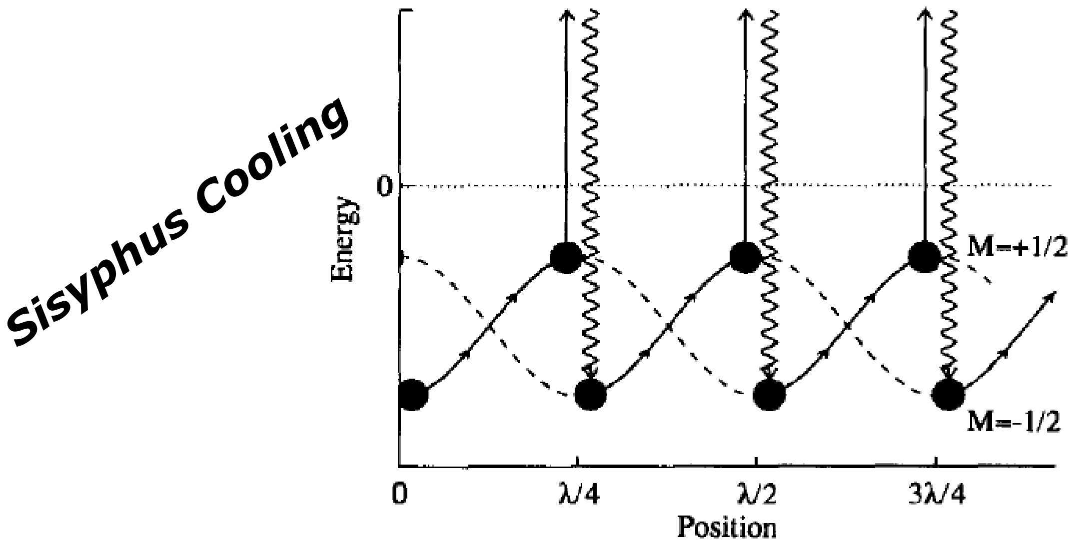


FIGURE 8.1. The spatial dependence of the light shifts of the ground-state sublevels of the $J = 1/2 \Leftrightarrow 3/2$ transition for the case of the lin ⊥ lin polarization configuration. The arrows show the path followed by atoms being cooled in this arrangement. Atoms starting at $z = 0$ in the $M_g = +1/2$ sublevel must climb the potential hill as they approach the $z = \lambda/4$ point where the light becomes σ^- polarized, and there they are optically pumped to the $M_g = -1/2$ sublevel. Then they must begin climbing another hill toward the $z = \lambda/2$ point where the light is σ^+ polarized and they are optically pumped back to the $M_g = +1/2$ sublevel. The process repeats until the atomic kinetic energy is too small to climb the next hill. Each optical pumping event results in absorption of light at a lower frequency than emission, thus dissipating energy to the radiation field.

Circular Polarized light

- Counter propagating oppositely circularly polarized light beam.
- There is no temporal phase difference between the two polarization directions at any position.
- This represent a linear polarized field whose ε vector is fixed in time but rotates uniformly in space along *z*.

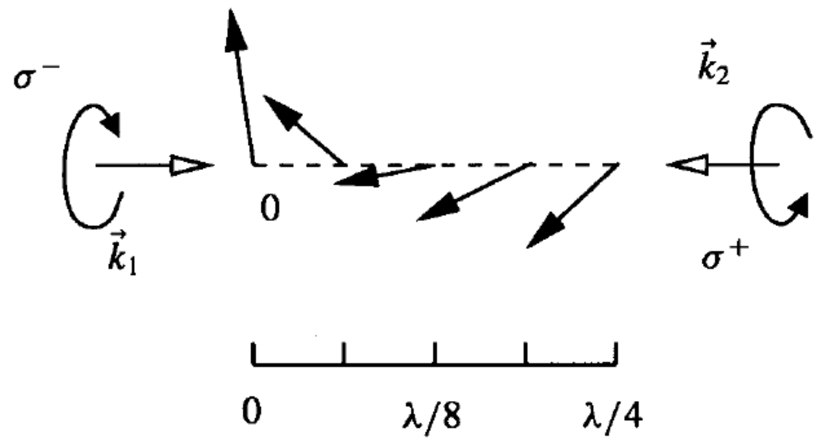


FIGURE 4.6. Polarization gradient field for the σ^+-σ^- configuration (see also Chapter 8).

Sub-Doppler cooling with circular polarized light

- No more "Sisyphus" effect, no hills and valleys.
- atoms at rest in the light field optical pumping redistributes the population among the magnetic substates.
  - $M_g=0$ will be populated more strongly then $M_g=\pm 1$
- Moving atoms experience rotation of the quantization axis, and must be optically pumped in order to follow it.
  - $M_g=+1$ is more populated then $M_g=-1$ for atoms traveling toward the beam with σ^+ polarization.
  - Vise versa for atoms traveling in the opposite direction
  - $M_g=1$ scatters the σ^+ light six times more efficiently them the σ^- light.
  - And the opposite for σ^- and $M_g=-1$.
- This effect cusses better cooling because the atoms want to interact with the other beam, due to different population in the sublevels.

Recoil Limit

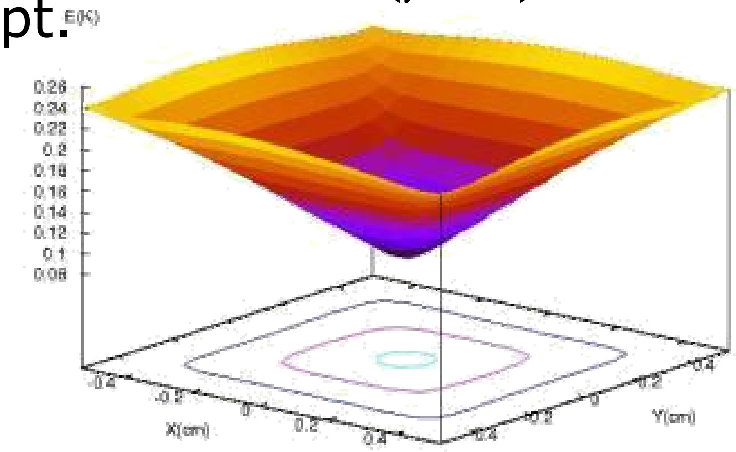
- The minimum steady state kinetic energy of a atom is E_r from two reasons:
  - the last spontaneous emission will leave the atom with radial momentum $hk/2\pi$ in a random direction.
  - The polarization gradient requires the atoms to be localizable within the scale of $\sim\lambda/2\pi$

$$E_r \equiv kbT_r = (\hbar k)^2 / 2M$$

Magnetic Trapping of Neutral Atoms

- H. Metcalf. *J. Opt. Soc. Am. B* **6**, 2206-2210 (1989)
- This trap is combination of an Optical trap as seen previously and a Magnetic trap.
- Neutral atoms need to in the ground or metastable state with magnetic dipole moment.
- The trap has a minimum therefore has return force.
- Atoms first be cooled down optically then can be trap magnetically.
- Ultra high vacuum must be kept.

$$\vec{F} = \vec{\nabla}(\vec{\mu} \cdot \vec{B})$$



Magneto-Optical Traps

- H. Metcalf. *J. Opt. Soc. Am. B* **6**, 2206-2210 (1989)
- The MOT is a very robust easy to construct trap.
- A MOT is created by using 3 pair of counter laser beams and inhomogeneous magnetic trap $B_{(z)} \cong Az$.
- *The Temperature of atoms in a MOT is in the μK range.*

  - The total force on the atom is:
  - δ - is the detuning for each laser beam.
  - μ - the effective magnetic moment for the transition used:
  - *Where Doppler and Zeeman shifts are small compeer to the detuning:*

$$\vec{F}_{fast-atoms} = \vec{F}_{+} + \vec{F}_{-}$$

$$\vec{F}_{\pm} = \pm \frac{\hbar \vec{k} \gamma}{2} \frac{s_0}{1 + s_0 + (2\delta_{\pm} / \gamma)^2}$$

$$\delta_{\pm} = \delta \mp \vec{k} \cdot \vec{v} \pm \mu' B / \hbar$$

$$\mu' \equiv (g_e M_e - g_g M_g) \mu_B$$

$$\vec{F}_{far-atoms} = -\beta (\vec{v} + \frac{\mu' A}{\hbar k} \vec{r})$$

1D MOT

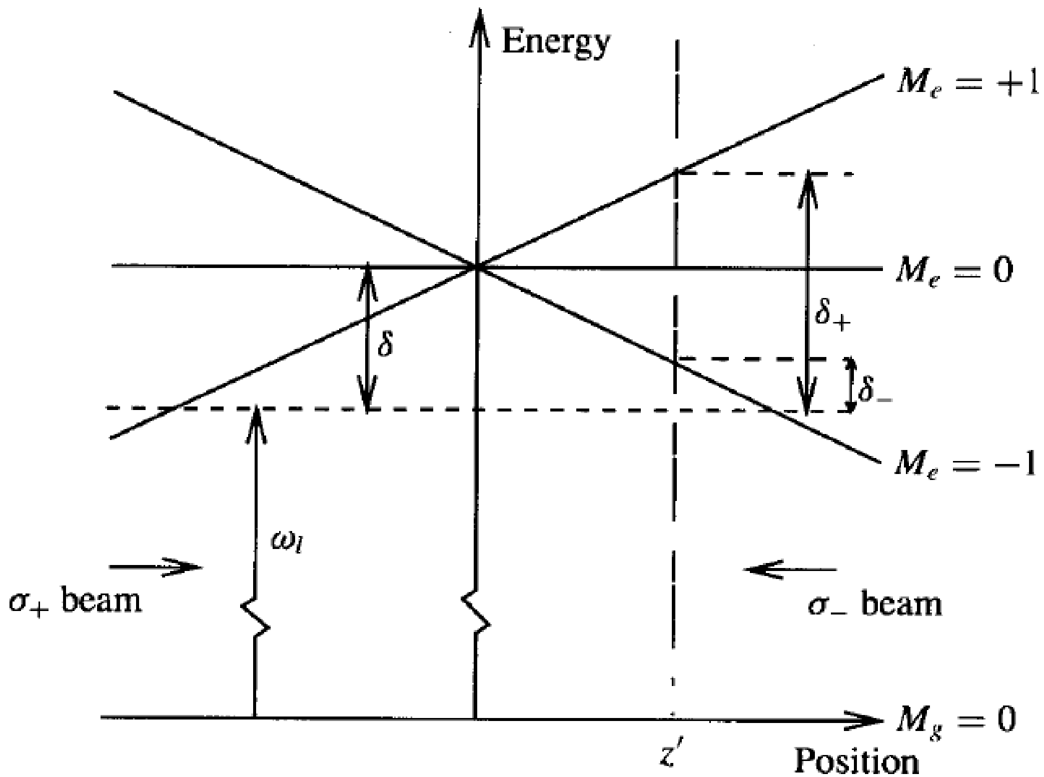
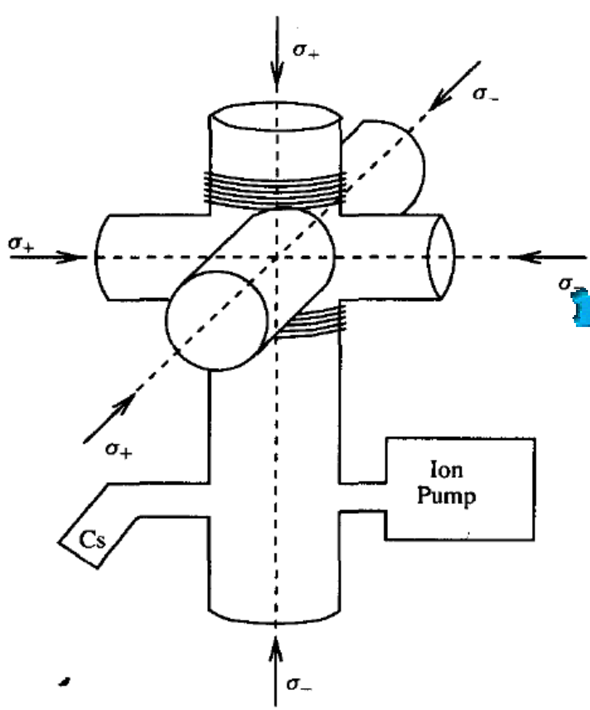


FIGURE 11.4. Arrangement for a MOT in 1D. The horizontal dashed line represents the laser frequency seen by an atom at rest in the center of the trap. Because of the Zeeman shifts of the atomic transition frequencies in the inhomogeneous magnetic field, atoms at $z = z'$ are closer to resonance with the σ^- laser beam than with the σ^+ beam, and are therefore driven toward the center of the trap.

3D MOT

- Repumping is achieved by tuning the repumper to the *Fg=2* $\rightarrow$ *Fe=1* transition.



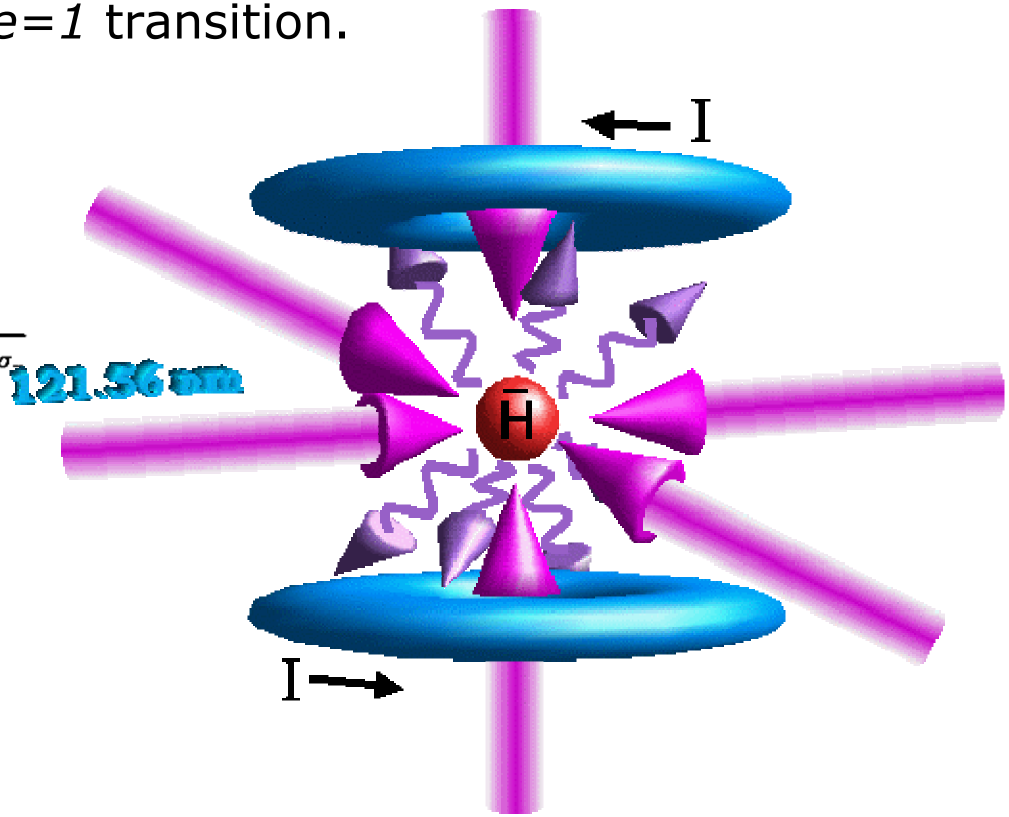
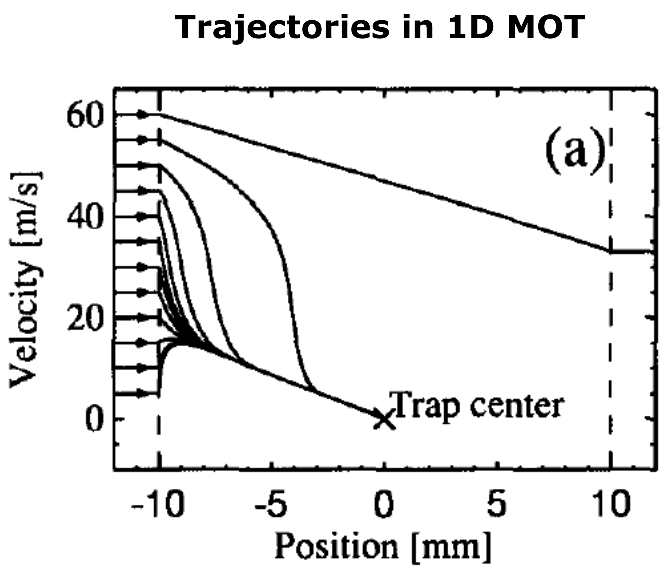


FIGURE 11.6. The schematic diagram of a MOT shows the coils and the directions of polarization of the six light beams. It has an axial symmetry and various rotational symmetries, so some exchanges would still result in a trap that works, but not all configurations are possible. Atoms are trapped from the background vapor of Cs that arises from a piece of solid Cs in one of the arms of the setup.

Capturing Atoms in a MOT



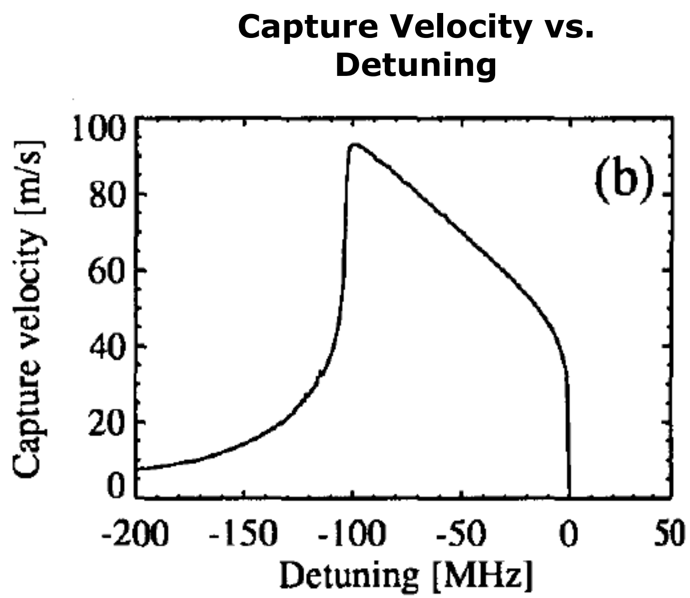
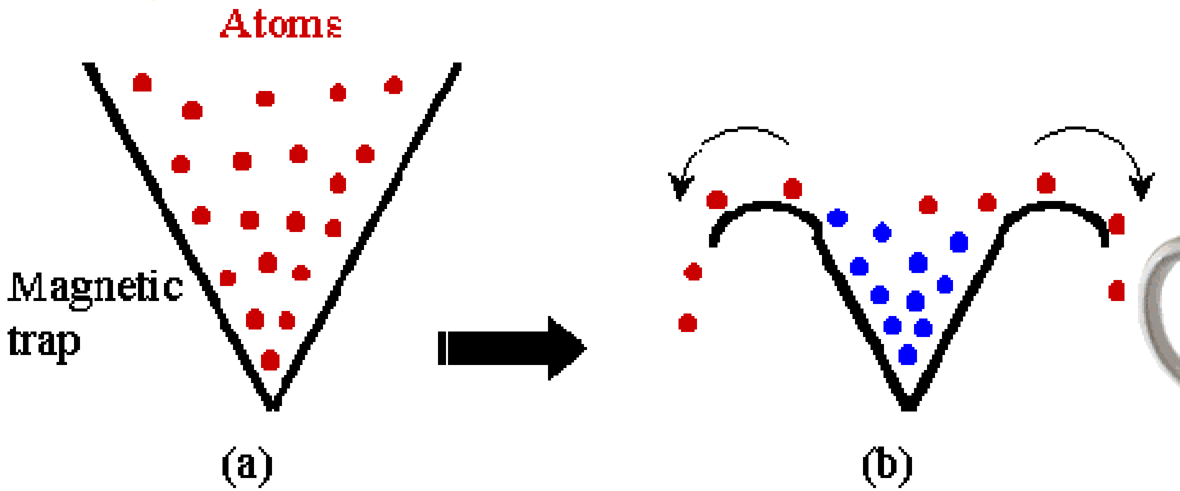


FIGURE 11.5. Numerical simulation of the capture process in 1D of the MOT for a $J_g = 0 \rightarrow J_e = 1$ transition. (a) Trajectories for Na atoms with such a simplified structure entering the MOT region with different initial velocities, which is increased between different trajectories by 5 m/s. Here s_0=10 and $\delta = -30$ MHz. For low enough velocities the atoms are collected in the center of the trap and remain trapped. (b) Dependence of the capture velocity v_c on the detuning of the laser from resonance. The largest v_c is obtained for a detuning of ≈ -100 MHz $\approx -10\gamma$.

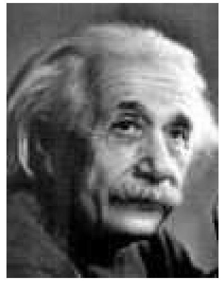
Evaporative Cooling

- Evaporative cooling works by the preferential removal of atoms having an energy higher then the average energy.
- The atoms magnetic moment -μB pushes them to the minimum of the trap.
- By changing the trap depth it is possible to release the hot atoms.
- Evaporative cooling applet



Bose-Einstein Condensation in a gas: a new form of matter at the coldest temperatures in the universe...

S. Bose



A. Einstein

- The Pathway to BEC:
  - Using MOT to capture atoms (only the slow ones).
  - Turn off the Magnetic trap and turn on the Optical Molasses till the atoms reaches the recoil temperature.
  - Evaporative Cooling: Turn off the OM and turning on the Magnetic trap for EC.
  - After this stage 1% of the atoms are in BEC state.
- The criteria for BEC:

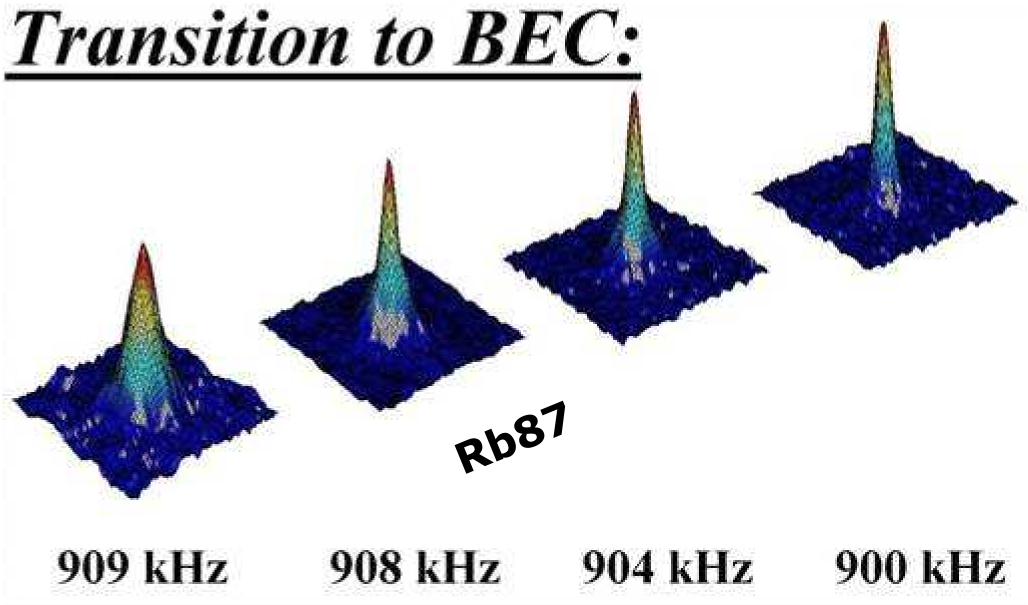
$$\rho \equiv n\lambda_{dB}^{3} \geq 2.612$$

$$\lambda_{dB} = h / M\vec{v} = h / \sqrt{3Mk_B T}$$

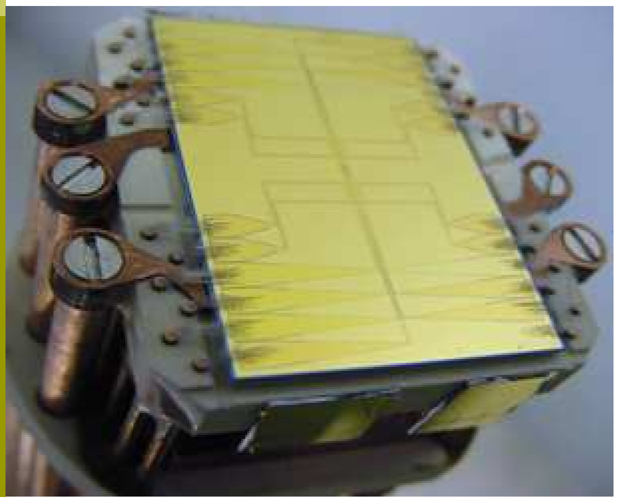
$$n \geq 2.612 \frac{\left(3Mk_B T\right)^{3/2}}{h^3}$$

BEC at Ben Gurion

- On April 11, 2007, we obtained Bose-Einstein Condensation (BEC) for the first time on our Atom Chip.



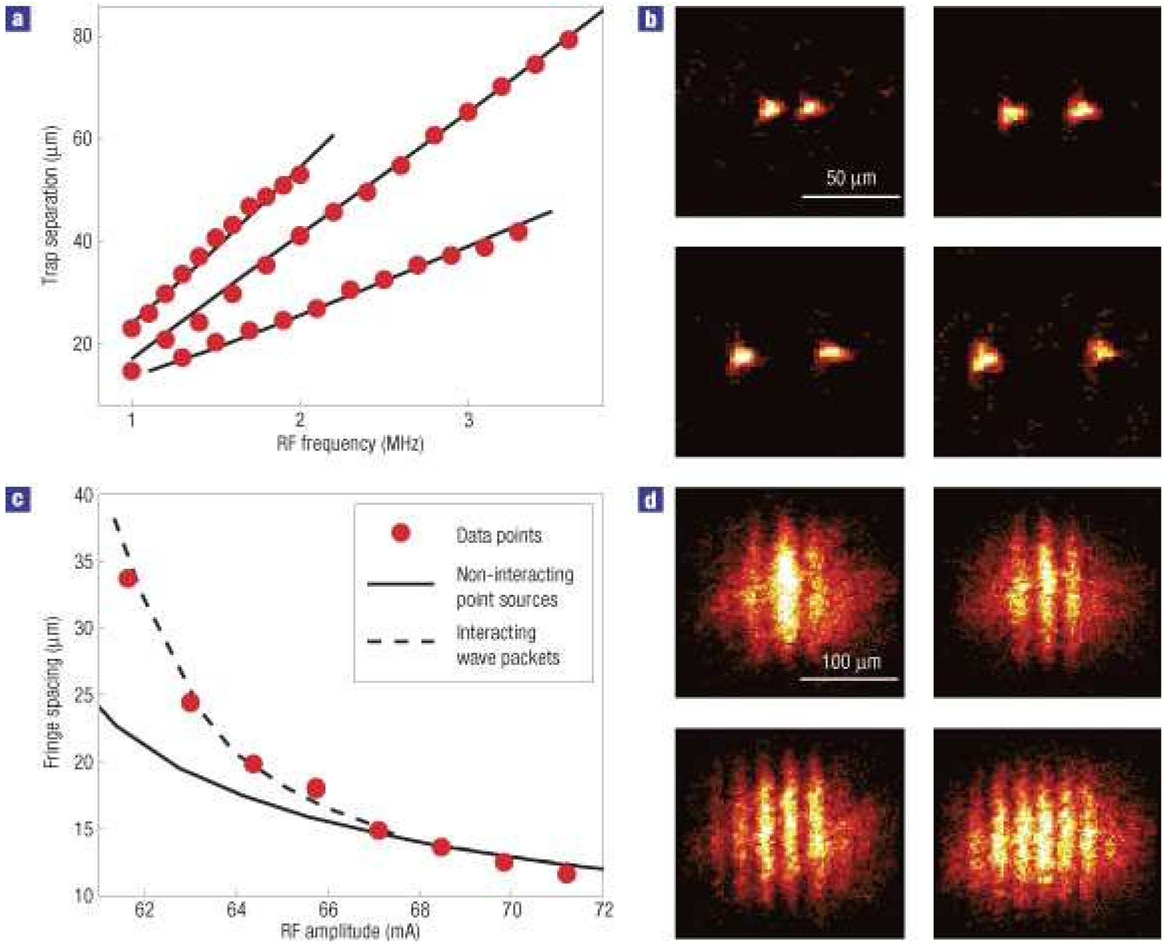
Our Atom Chip



http://www.bgu.ac.il/atomchip/physics/BEC.htm

BEC Interference fringes

- Interference fringes from two BEC who collides. The last picture took after 14ms of potential free TOF.



[Matter-wave interferometry in a double well on an atom chip]

T. Schumm, S. Hofferberth, L. M. Andersson, S. Wildermuth, S. Groth, I. Bar-Joseph, J. Schmiedmayer and P. Krüger

***Nature Physics* 1, 57 - 62 (2005)**

Dipole Force Optical Traps

- S. Chu *et-al. Phys. Rev. Lett. 57*, 314 (1986)
- What happens if a laser beam has spatial inhomogeneity in power?
- The Stark shift has spatial differences.
- Atoms will "run" to the minimum.
  - With laser light tuned bellow resonance, the light shift is everywhere negative, but larges at the center of the Gaussian beam waist.
  - With blue detune laser the maximum is at the maximum intensity.

$$I_{(r)} = I_0 e^{-r^2/w_0^2}$$

$$F \approx -\frac{\hbar}{4\delta}\nabla\left(\Omega_{(r)}^2\right) = -\frac{\hbar\gamma^2}{8\delta I_S}\nabla I_{(r)}$$

$$F \approx -\frac{\hbar\gamma^2}{4\delta}\frac{I_0}{I_S}\frac{r}{w_0^2}e^{-r^2/w_0^2}$$

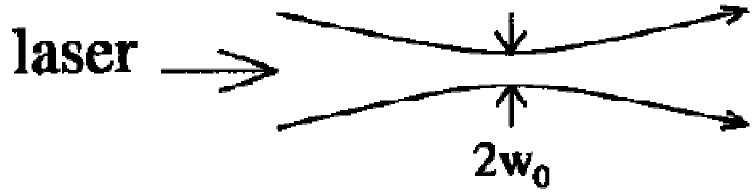
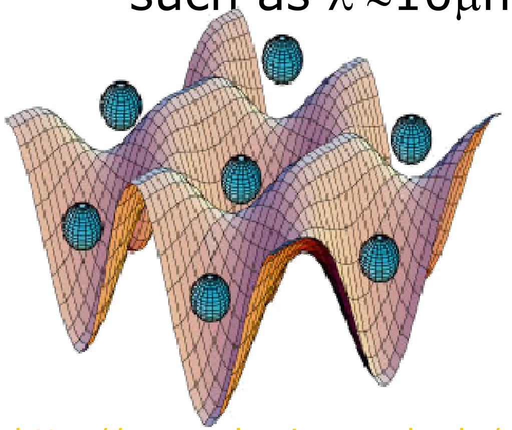


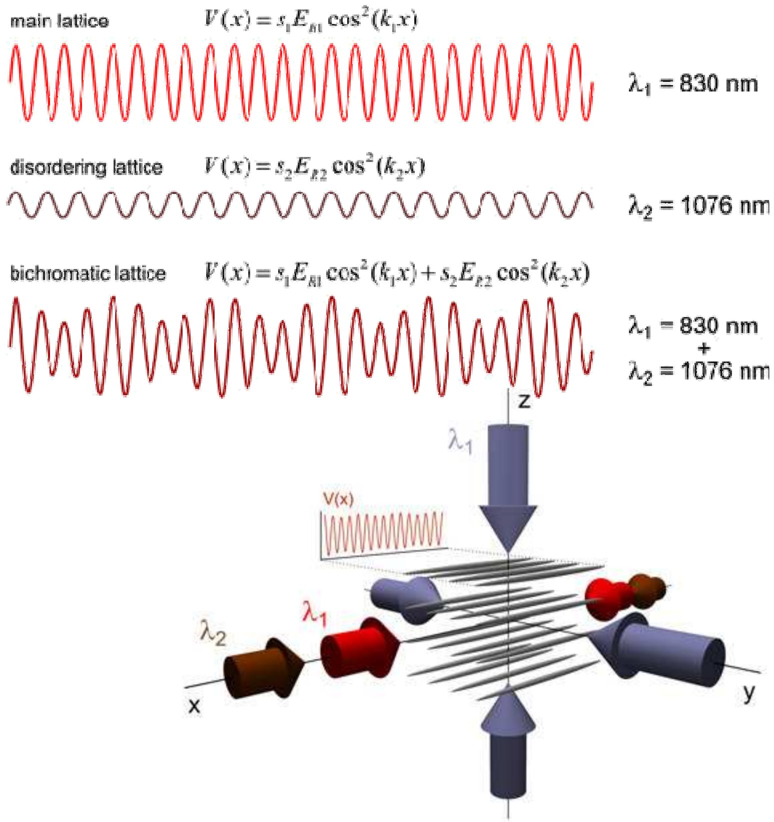
FIGURE 11.1. A single focused laser beam produces the simplest type of optical trap.

Optical Lattices

- Using few lasers with different frequency creates "egg-crate" potential.
- The potential walls are separated by $\lambda/2$,and the lattice site density is a few 10^{13} cm^{-3} .
- Loading of atoms into the lattice is typically done from sample of trapped and cooled atoms.
- OL usualy been created by using long wavelength lasers far off resonance such as $\lambda \approx 10\mu m$ CO_2 .



http://www.physics.umd.edu/news/photon/iss033/images/opticallattice1.jpg



LENS

http://quantumgases.lens.unifi.it/?q=node/87

Laser Arrangements for Optical Lattices

- This is a simple technique for creating 1D lattice.
- sub-wavelength vibrations of the mirrors changed the relative phase of the mirrors and made dramatic changes in the local polarization.

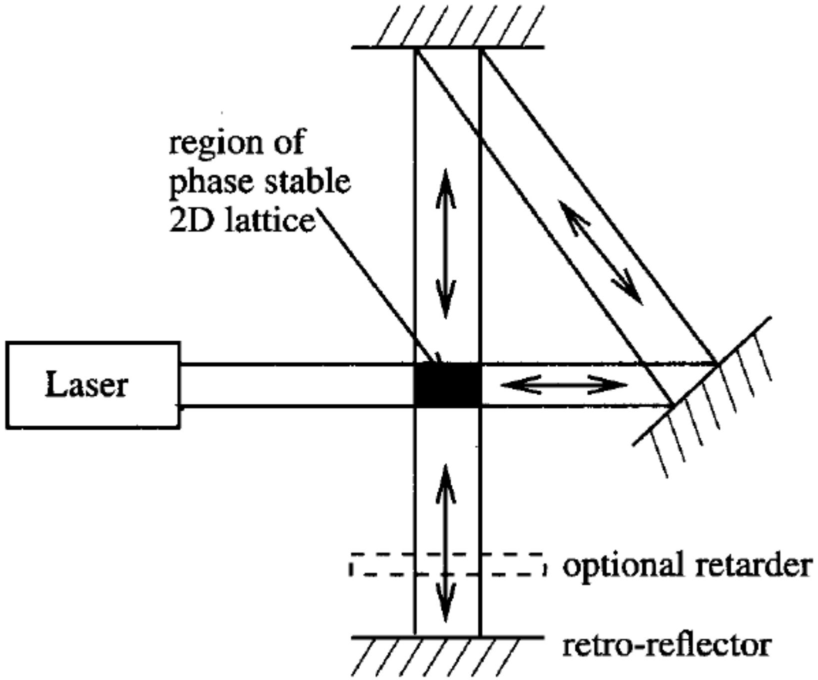


FIGURE 16.2. A single mode of a standing wave cavity is folded by mirrors to make an optical field consisting of two perpendicular phase-stable standing waves. Their polarizations can be different by placement of a retarder at the indicated position [316].

Some new Experiments