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Seminar II

Laser cooling of atoms

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Abstract

This paper presents an overview of a basic cooling process needed to achieve Bose-Einstein condensation in an atomic gas. Techniques like Zeeman slower, optical molasses, magneto-optical trap, Raman sideband cooling and evaporative cooling are described along with a general description of Bose-Einstein condensate.

Contents

1 Introduction

Since Bose-Einstein condensation was first achieved in 1995, the field of cold atom gases has flourished. Researchers have shown that Bose-Einstein condensates (hereafter denoted as BEC) interfere, can be used as coherent source for atomic laser [1], to study properties of solid state systems and improve accuracy of atomic clocks. They offer a unique opportunity to study fundamental quantum mechanic phenomena such as superfluidity and formation of quantum vortices. Boson gas can be used as a medium to cool fermionic gas to the point of Fermi sea, which allows the study of the connection between BEC and BCS theory of superconductivity [2]. Creation of molecules of atoms in ultracold gases is also possible, and then creating a Bose-Einstein condensate of these molecules.

In order to achieve that a lot of different cooling techniques had to be developed. We generally separate them into two categories: laser cooling, which relies on atom scattering of photons and evaporative cooling, which can be performed in either a magnetic or electric dipole trap. In this seminar I give a quick review of main cooling techniques necessary to achieve BEC, such as Zeeman slower, optical molasses, magneto optical trap, Raman sideband cooling and evaporative cooling.

2 BEC

Bose-Einstein condensate is a state of matter in which all the particles occupy the ground energetic state. In order to achieve Bose-Einstein condensation a boson gas must have a large enough density at a low enough temperature. This happens when number density reaches the value [3]:

$$n = \frac{2.6}{\lambda_{dB}^3}, \tag{1}$$

where λ_{dB} is the de Broglie wavelength defined by

$$\lambda_{dB} = \frac{h}{\sqrt{2\pi M k_B T}}, \tag{2}$$

where M is a mass of an atom, T is the temperature, and h and k_B are Planck and Boltzmann constant, respectively. The de Broglie wavelength represents position uncertainty of the particles and defines a volume in which we are likely to find an atom. When this volume becomes large enough, i.e. λ_{dB} becomes comparable to the distance between atoms, Bose-Einstein condensation occurs and individual wavefunctions all become one matter wave, as shown in Figure 1.

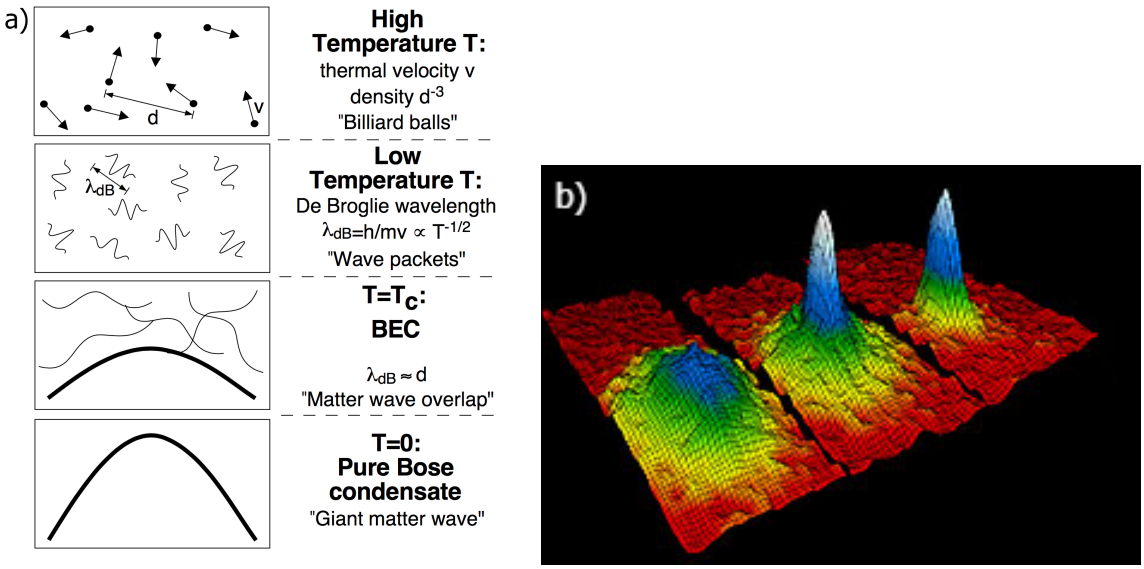

Figure 1: a) At high temperatures atoms in a weakly interacting gas behave like hard spheres. As the gas is cooled down we describe them quantum mechanically as wavepackets of length λ_{dB}. λ_{dB} becomes comparable to the distance between atoms at the BEC transition temperature and as we lower the temperature further towards zero all the atoms form a giant matter wave [4]. b) This transition is also noticeable in the right picture that shows the first experimental observation of a BEC in Boulder [5].

3 Cooling techniques

In order to create a BEC a number of cooling techniques needed to be developed. We can divide them into two categories: laser cooling and evaporative cooling. First laser cooling is used to slow down the atoms enough to load them into a dipole or magnetic trap, where forced evaporation is performed.

3.1 Laser cooling

Laser cooling relies on the force photons exert on atoms in the scattering process. The scattering force is [3]

$$F_{scatt} = \hbar k \frac{\Gamma}{2} \frac{I/I_{sat}}{1 + I/I_{sat} + 4\delta^2/\Gamma^2}, \tag{3}$$

where $\hbar k$ is photon's momentum, Γ the transition rate between two atom levels, I the intensity of incident light, $I_{sat}(\omega) = \hbar\omega A_{21}/(2\sigma(\omega))$ the saturation intensity, where A_{21} and $\sigma(\omega)$ are the Einstein rate coefficient for spontaneous emission and the absorption cross-section, respectively. The scattering force lastly depends on the frequency detuning from resonance, $\delta = \omega - \omega_0 + kv$, where ω is the frequency of the incident photon, ω_0 is the transition frequency between two atomic levels and $kv = \frac{2\pi}{\lambda}v$ is the Doppler shift of this frequency for an atom moving at velocity v in the direction opposite to that of a laser beam (as shown in Figure 2a).

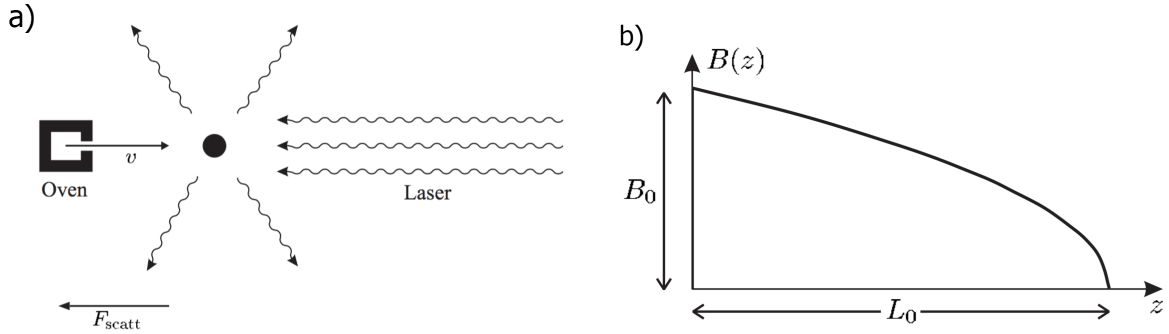

Figure 2: a) Atom emitted from an oven at velocity v is shone on with a laser beam. Atom absorbs laser photons and scatters them in random directions. Averaged over many scattering events the effect of the scattered photons cancels out and total momentum gain points in the direction of the laser beam, therefore the atom slows down. b) Parabolic profile of the magnetic field is needed to compensate Doppler shift along the atomic beam [3].

3.1.1 Zeeman slower

When an atom loses velocity because of laser cooling, the Doppler shift of transition frequency changes and the effect of laser light diminishes. To counter this, a clever experimental technique called Zeeman slowing has been developed. As we know, atomic energy levels can be perturbed

using magnetic field. This is called the Zeeman effect. If the right profile of magnetic field is chosen (shown in Figure 2b) it cancels out the Doppler shift, and laser light of constant frequency can be equally effective along the entire path of the atom. This technique can bring the atoms to almost a complete stop, with temperatures of only a few kelvins, prepared for the next step in the cooling scheme.

3.1.2 Optical molasses

At the end of the Zeeman slower coil, atoms are slow enough that they no longer move only in the direction along the beam but in all three spacial directions. One laser beam is no longer sufficient to slow them down. Three pairs of counter propagating beams are needed (one pair along each of the x, y and z axes). The laser frequency is chosen so that the atoms moving towards the laser are in resonance and those moving away are off resonance by $2kv$, where $k = \frac{2\pi}{\lambda}$ is the wave vector of light (Figure 3a). Dependence of force on velocity of the atoms is shown in Figure 3b. We can see that it is always opposite to the direction of the velocity and therefore damps the movement of atoms. We also see that stationary atoms experience no force because they are off resonance too (by kv).

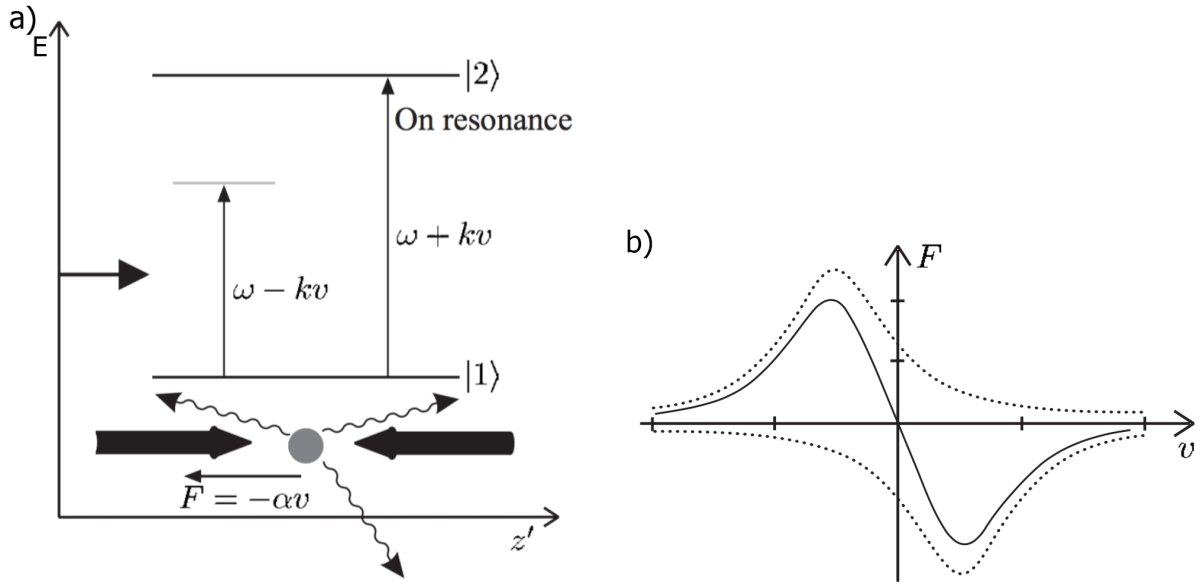

Figure 3: a) Light can scatter off an atom moving in opposite direction of the laser beam but not off an atom moving along the laser beam. b) Force dependence on velocity in optical molasses is such that moving atoms always slow down and stationary atoms don't feel the force at all [3].

But we cannot cool the atoms to arbitrarily low temperatures with this technique. It is limited by the so called Doppler cooling limit which is a consequence of random momentum kicks because of spontaneous emission and because absorption is random and therefore the atom doesn't always absorb the same number of photons in a given time interval. This limits the cooling of two-level

atoms to [3]:

$$k_B T_D = \frac{\hbar\Gamma}{2}. \tag{4}$$

For Cs D_2 transition used in our experiment [6] we get the Doppler limit $T_D = 125$ μK (for data taken from [7]). Luckily this model is only accurate for two-level atoms. For real atoms optical molasses actually works better than this model predicts and atoms can be cooled to a few μK. Better sub-Doppler cooling techniques, such as Raman sideband cooling can cool the atoms even under 1 μK.

3.1.3 Magneto-optical trap (MOT)

Optical molasses slows down the atoms, but does not confine them. To create a MOT, atom cloud is placed in a quadrupole magnetic field generated by a pair of magnetic coils with currents in opposite directions (Figure 4b). In the example shown in Figure 4a, the energies of the three sub-levels of state $J = 1$ split because of the Zeeman effect caused by the quadrupole field. Magnitude of the split increases linearly with the distance from the center of the quadrupole coils.

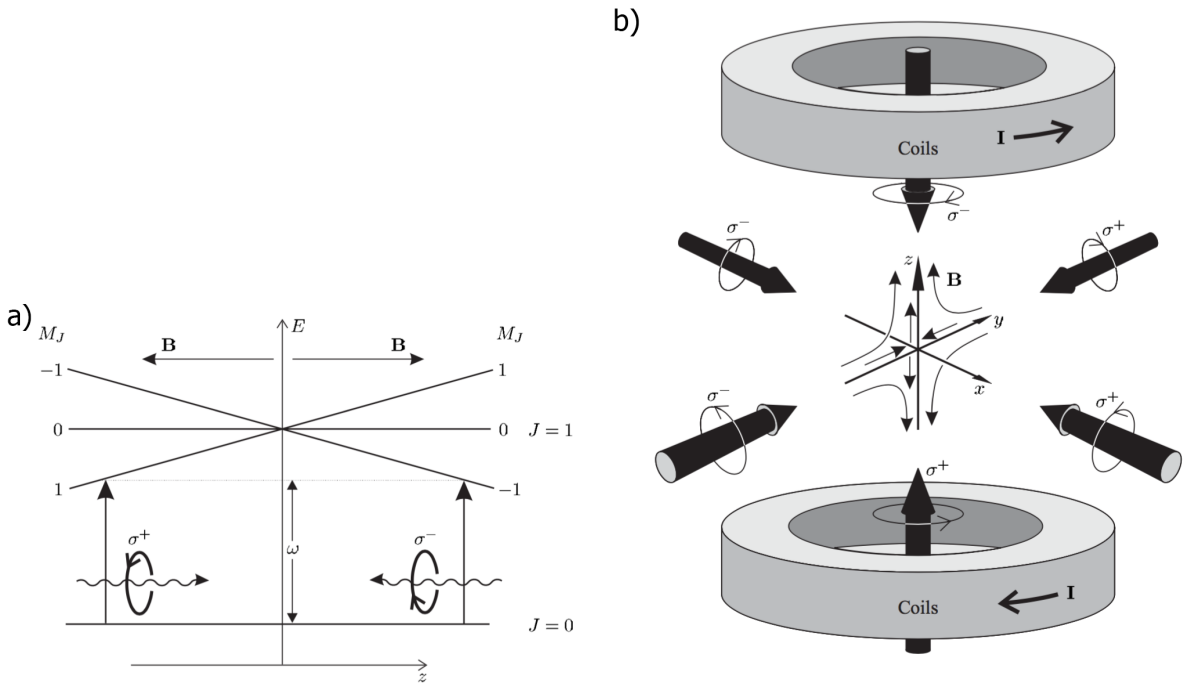

Figure 4: a) Sub-levels of the $J = 1$ state are split due to the Zeeman effect caused by a quadrupole magnetic field. Laser frequency is detuned so it only affects atoms away from the center of the field. b) Coil and beam configuration of a MOT. The coils create the quadrupole field in the middle of the trap and circularly polarized beams strongly confine the atomic cloud [3].

In order to trap the atoms, polarization of the beams must be changed to circular. Each pair of counter propagating beams consists of a clockwise circularly polarized σ^+ that drives transition

$|J = 0, M_J = 0\rangle \rightarrow |J = 1, M_J = 1\rangle$, and an anticlockwise circularly polarized σ^- that drives transition $|J = 0, M_J = 0\rangle \rightarrow |J = 1, M_J = -1\rangle$. Laser frequency is detuned from the resonance at the center of magnetic field so that the transition $\Delta M_J = \pm 1$ becomes resonant further away from the coil center and the atoms get pushed back towards the middle if they wander to far away from the center of the trap (Figure 4a). When a sufficient number of atoms is trapped, the MOT is turned off in order to cool the atoms in the optical molasses before the next cooling stage.

3.2 Evaporative cooling

Laser cooling techniques by themselves are not sufficient to reach the BEC. To cool the atoms further, the MOT is compressed and loaded into a magnetic or dipole trap. I only describe the mechanism of the dipole trap since it is used in our laboratory. The evaporation itself is very similar for both magnetic and dipole traps. In the experiments with cesium atoms there is an additional intermediate stage between the MOT and evaporative cooling called Raman sideband cooling, which I describe in greater detail later in this text.

3.2.1 Dipole force

Refracting light exerts a force on the object it is passing through. This is nicely illustrated for a light beam passing through a glass prism in Figure 5a. The force on the object depends on the intensity of the light beam and on the refractive index of the material. If we put a glass sphere into a Gaussian beam, the resultant of the force points in the direction of higher intensity, as is shown in Figure 5b. If the refractive index of the sphere were smaller than that of the surrounding medium, the force would push it away from the center of the beam.

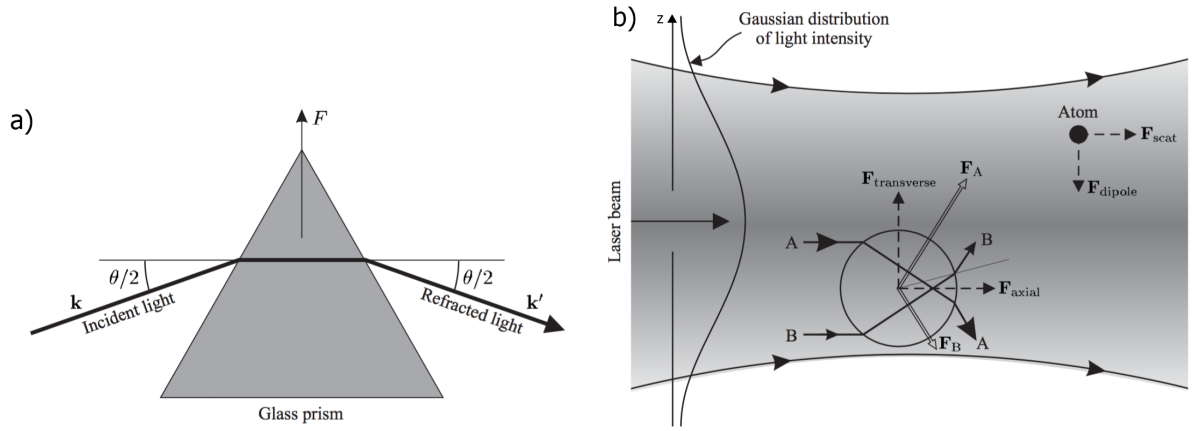

Figure 5: a) Force exerted by a refracting beam on a glass prism. b) Illustration of dipole force for a glass sphere in a Gaussian beam. Because of the intensity gradient the sphere is drawn towards the region of high intensity [3].

A similar force acts on atoms put in a gradient electric field. Light induces a dipole moment in the atom, which in turn interacts with the electric field. If the light is red detuned from the atomic

transition frequency, atoms are drawn towards the higher intensities and if it is blue detuned, they are repulsed.

In a standing wave of light the dipole force is particularly strong, because the intensity changes from minimum to maximum over a short distance ($\lambda/2$). This is taken advantage of in optical lattices used for Raman sideband cooling.

3.2.2 Forced evaporation

In the experiment, the dipole trap is created by crossing two strong, red detuned laser beams. In addition to that, a strong enough magnetic field gradient must be created to levitate the atoms, because the dipole trap by itself is not sufficient to counteract gravity. Atoms trapped in the dipole trap have a Boltzmann energy distribution at temperature T_1: $\mathcal{N}(E) = \mathcal{N}_0 \exp(-\frac{E}{k_B T_1})$ (Figure 6c). The fastest atoms with energies $E > E_{cut}$ are allowed to escape (figures 6b and 6d) and the remaining ones re-thermalize at a lower temperature $T_2 < T_1$ (Figure 6e). During evaporation the atomic density increases, because atoms with lower energy sink deeper into the trap. This triggers runaway evaporation, i. e. an increasing collision rate, which greatly reduces the temperature and increases phase space density to a point where quantum effects become important. This is the last step in the cooling process and has proven successful in creating a BEC.

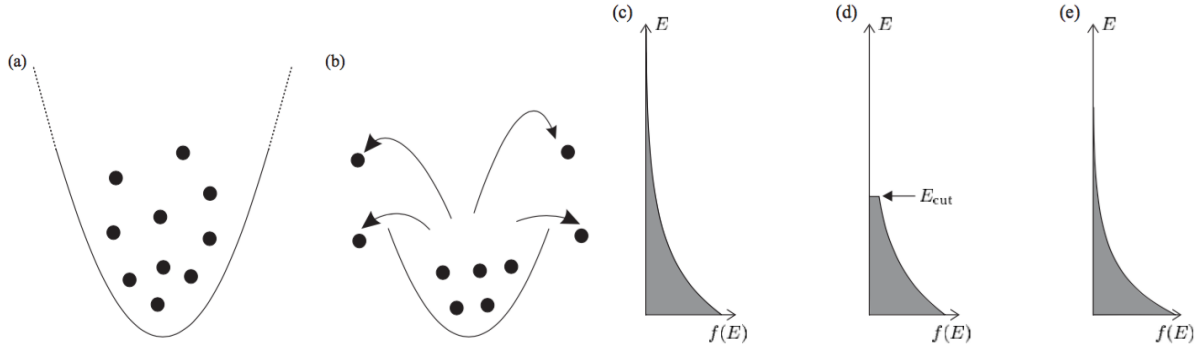

Figure 6: a) Atoms trapped in a dipole trap, b) the fastest atoms are allowed to escape, c) initial Boltzmann distribution of energies $\mathcal{N}(E) = \mathcal{N}_0 \exp(-\frac{E}{k_B T_1})$, d) distribution of energies immediately after the fastest atoms have escaped, e) final distribution of energies after re-thermalization at $T_2 < T_1$ ($\mathcal{N}(E) = \mathcal{N}_0 \exp(-\frac{E}{k_B T_2})$) [3].

3.3 Raman sideband cooling

Temperature needed to load atoms into the dipole trap without significant losses is below 1 μK and cannot be achieved in the MOT. This is solved by implementing an additional cooling step called Raman sideband cooling. Besides cooling the atoms it also selects the right hyperfine state, $|F = 3, m_F = 3\rangle$, in which the atoms can be levitated while trapped in the dipole trap. $\mathbf{F} = \mathbf{J} + \mathbf{I}$ is the total atomic angular momentum, where $\mathbf{J}$ and $\mathbf{I}$ are the total electron and the total nuclear angular momentum, respectively. Its magnitude is $|\mathbf{F}| = \hbar\sqrt{F(F+1)}$, where F can take the values: $|J-I| \leq F \leq J+I$, and its projection m_F can take the values $\{-F, -F+1, \ldots, F-1, F\}$.

3.3.1 Raman transitions

Raman transition is a two photon transition consisting of absorption and stimulated emission. Figure 7a shows an atom moving with velocity v, that absorbs a photon of frequency ω_{L1}, exciting it into a virtual state Δ detuned from the upper level $|i\rangle$. Immediately, another photon with frequency ω_{L2}, travelling in the opposite direction causes stimulated emission of the photon into state $|2\rangle$. This allows for precise selection of atoms with a velocities that satisfy the equation [3]:

$$\frac{v}{c} = \frac{\omega_{12} - (\omega_{L1} - \omega_{L2})}{\omega_{L1} + \omega_{L2}}, \tag{5}$$

where c is the light speed and ω_{12} is the frequency of $|1\rangle \rightarrow |2\rangle$ transition.

3.3.2 Raman cooling

Lets take a look at how we can use Raman transitions to cool atoms. This is schematically shown in Figure 7b-e. First we use Raman pulse to transfer atoms with velocity v into level $|2\rangle$ (Figure 7b). In the process atoms lose twice the recoil velocity v_r (this is a velocity gained/lost by absorbtion/emission of one photon). In the second step, shown in Figure 7c, another laser is used to excite the atoms from level $|2\rangle$ to level $|i\rangle$. From there they decay back to level $|1\rangle$ with velocities centered around $v - v_r$ (Figure 7d). Thus by the end of the cycle we have more atoms in an interval $[-\delta v, \delta v]$ than in the beginning.

The cycle is repeated many times for different initial velocities, avoiding those around zero, and in the end we get a very narrow velocity distribution shown in Figure 7e. This basic scheme would work well in one dimension, but in practice where we have to lower velocities in all three directions, it doesn't prove to be very efficient.

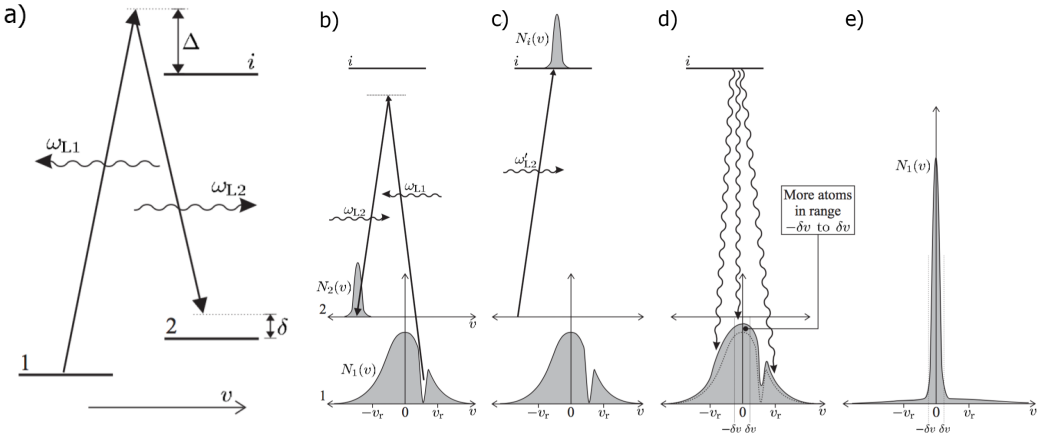

Figure 7: a) Raman transition between atomic levels 1 and 2. First a photon of frequency ω_{L1} excites the atom into a virtual state and then another photon ω_{L2} is emitted and the atom ends up in state 2. b) Raman transition $|1\rangle \rightarrow |2\rangle$ causes atoms to lose $2v_r$, c) they are transferred into state $|i\rangle$ by a third laser beam, d) from which they decay back into state $|1\rangle$ with velocities centered around $v - v_r$. e) Velocity distribution after many cooling cycles [3].

3.3.3 Optical lattice

Raman sideband cooling in practice takes place in an optical lattice. Four laser beams of appropriately chosen polarisation are crossed at the position of the MOT (red beams in Figure 8a) and the interference pattern they create is an optical lattice (Figure 8b shows an interference pattern for a 2D lattice). The dipole potential of the lattice traps the atoms; usually only one atom per lattice site. If the lattice is deep enough, atoms are tightly bound and we can treat them as if they are each in a harmonic oscillator with vibrational energies $E_n = \hbar\omega_{HO}(n + 1/2)$.

Everything is placed in a small magnetic field, which splits the hyperfine levels of the atom so that the vibrational energies of neighbouring states are degenerate (Figure 9b):

$$E_n(m_F = 3) = E_{n-1}(m_F = 2) = E_{n-2}(m_F = 1). \tag{6}$$

This enables lattice beams to drive Raman transitions between neighbouring m_F states and thus lowering their vibrational energies.

The goal is to get the atoms into the lowest possible state, i. e. $|m_F = 3, n = 0\rangle$, and in order to do that another beam is needed to drive transitions between different m_F states. This polariser beam is σ^+ polarized with a small amount of π polarization (blue beam in Figure 8a). Its frequency is resonant with $|F = 3\rangle \rightarrow |F = 2\rangle$ transition in order to make $|F = 3, m_F = 3\rangle$ a dark state (Figure 9a). Atoms in $|F = 2, m_F = 2\rangle$ preferentially decay into $|F = 3, m_F = 3\rangle$ and eventually all of them end up there.

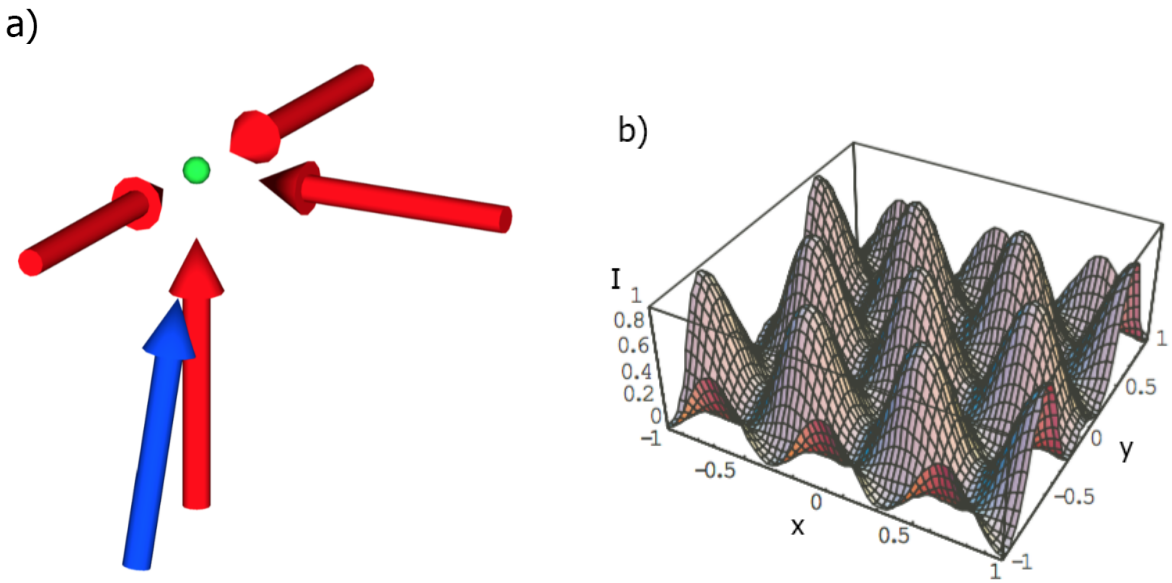

Figure 8: a) Beam configuration for Raman sideband cooling. Red beams create a 3D optical lattice and the blue one is polariser beam which pumps atoms between different m_F states [8]. b) Intensity pattern in a 2D optical lattice [9].

When we put a polariser beam and Raman lattice together, two step cooling occurs. Atoms in high vibrational states are transferred by Raman transitions from $|m_F = 3, n\rangle \rightarrow |m_F = 1, n - 2\rangle$

and then by σ^+ beam back to $|m_F = 3\rangle$, losing two vibrational quanta of energy. π component of the polariser beam doesn't play a major role at this point, because it is very weak compared to σ^+ component and the Raman lattice beams, therefore the rate of π transitions is much slower. This process repeats until the atom gets into $|m_F = 3, n = 1\rangle$ becoming dark to σ^+ beam. From this state Raman transitions and the π polarized beam slowly pump the atoms into a true dark state $|m_F = 3, n = 0\rangle$.

This produces very cold atoms, with temperatures below 1 μK, and prepares them in the right state to be levitated in a dipole trap.

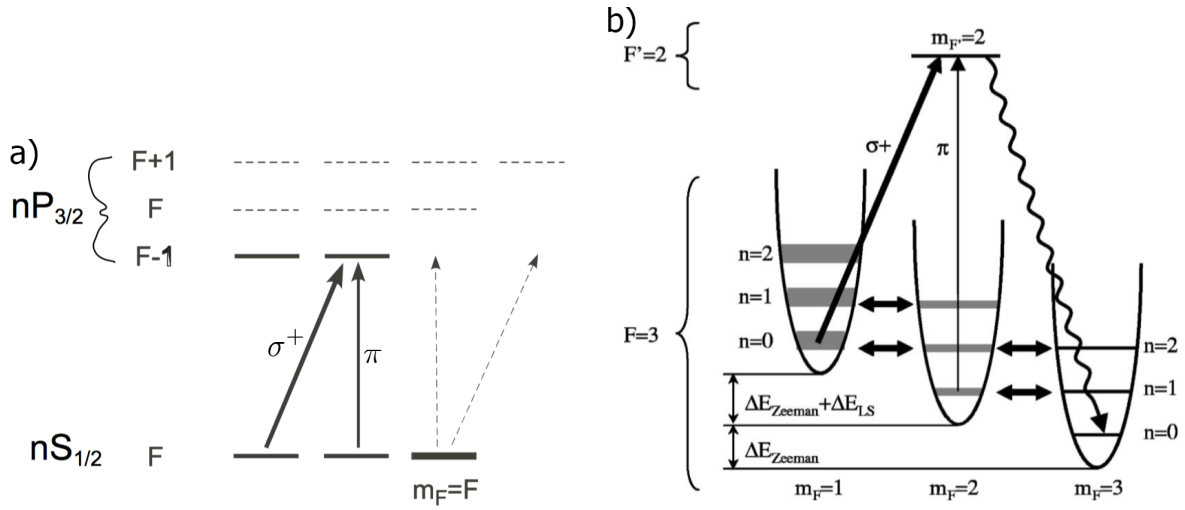

Figure 9: a) Optical pumping with the polariser beam between $|F\rangle$ and $|F-1\rangle$ states. The beam has a strong σ^+ component and a weak π component making $|m_F = F\rangle$ a dark state [9]. b) Two step cooling process. A magnetic field is chosen so that the vibrational levels between neighbouring m_F states are degenerate. Lattice beams drive Raman transitions between these states and the polariser beam pumps the atoms towards the m_F state with the lowest energy [10].

Now that I have described all of the cooling stages, lets take a look at the temperatures after each of them. The following table shows temperature and velocity after each cooling stage for our experiment with cesium atoms.

	Temperature	Velocity
Oven	360 K	260 $\frac{\text{m}}{\text{s}}$
Zeeman slower	3 K	24 $\frac{\text{m}}{\text{s}}$
MOT (optical molasses)	10 μK	4,3 $\frac{\text{cm}}{\text{s}}$
Raman sideband cooling	500 nK	9,7 $\frac{\text{mm}}{\text{s}}$
Dipole trap (BEC)	50 nK ?	3,1 $\frac{\text{mm}}{\text{s}}$

Velocities were calculated as the most likely velocity, $v = \sqrt{\frac{2k_BT}{m}}$, for an ideal gas with Maxwell-Boltzmann velocity distribution, with data taken from [7]. There is a question mark at the evaporative cooling stage, because a BEC has yet to be created. It is also important to note that once

Bose-Einstein condensation happens, the gas is no longer ideal, therefore the calculated velocity is incorrect.

4 Conclusion

A brief description of cooling techniques needed to achieve BEC was given. While they may seem quite straightforward in theory, experimental realization is far from simple and it takes even the greatest experts a few months to build the experiment capable of producing BEC from scratch. Our group is now at the last stage of the process and we hope to produce the condensate at any moment.

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