Analysis of the Principle and State-of-art Applications for Laser Cooling and Trapping

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Abstract. As a matter of fact, the laser cooling and trapping has already been widely used in various fields in advanced atoms controlling. With this in mind, this study gives a systematical analysis of the principle of laser cooling and trapping, and the development of them in the recent years. To be specific, this study will discuss the applications that has invented in the recent year based on the laser colling and trapping (especially for the state-of-art facilities), and makes a comparison between the concepts of laser cooling and laser trapping accordingly. Then, based on the analysis and evaluations, the limitations of laser cooling and laser trapping have been shown, and the future outlooks are also claimed and demonstrated as well. To sum up, the study concludes by discussing the limitations of these techniques, and gives some methods to solve these issues. Overall, these results shed light on guiding further exploration of laser cooling and trapping.

Keywords: Laser cooling, laser trapping, radiation pressure, Bose-Einstein condensate.

1. Introduction

In the past few decades, there has been an increasing interest in the use of laser cooling and trapping, and these technologies provide tools to the researcher to find their own directions for research outside the scope of an atomic experiment. It provides the basis for many of the modern experiment, such as the preparation of atomic Bose-Einstein condensate, and quantum dissipative process. Laser cooling and trapping produces excellent new tools for atomic physic [1]. In 1978, Ashkin wrote a paper to describe how one can slow down an atom by employing a laser beam that is adjusted to an atomic resonance to create radiation pressure. After the atom has been slowed, it would be caught in a trap made of concentrated laser beams with reduced the atomic movement until the temperature of it reached the range of microkelvin [2]. These technologies can help scientists do further researches in the atomic field.

During the first two decades of this outstanding method, the idea of cooling molecules has only been considered by a few people. Physicists had a strong interest in atoms, and may have considered molecules unhelpful complexity. While chemists are more familiar with molecules, they were not easily convinced that studying them at low temperatures was fascinating. In addition, the application of laser cooling methods on molecules was truly, for the first time, prohibitive. However, the situation has recently undergone a transformation. Now, methods have been developed by certain groups to make the atoms slow down and cool enough, and with the help of evaporative cooling that nearly reach the Bose-Einstein condensates. What's more, it has been reported that by transferring momentum from a counter-propagating resonant laser beam, a definitive observation of neutral atoms' deceleration and velocity bundled in a heated beam can be made. Laser beams have slowed down the ions trapped by electromagnetic fields, but they are not enough to restrict atoms for the similar cooling. Solving problems like transit time and SODE in atomic clocks and precision spectroscopy could be achieved by obtaining a sample of slow atoms. It's possible to use them for the scattering which has a very low energy, or deposit them in shallow traps for further cooling [3].

Examining the origin of optical trapping and the operation about the small particles, with particular attention given to the origins of the field, which did not even exist before the invention of lasers, is now playing an important role in the studies of unique particles in physics, and even biology and chemistry. It was well known from atomic physics and the beginnings of optics that light had linear and angular momentum. As a result, the light has the ability to give a radiation pressure on the objects

[4]. This effect, though it was really small, can be considered as radiation pressure forces, which have the same effects and still obey the classical mechanics. As a result, one can consider the light as a special kind force, and use it to help us manipulate small particles. This report is going to present a survey for the recent theoretical advances about the laser cooling and trapping, and also explain the principle of these technologies. Besides, the report will point out the shortages and disadvantages of the technologies, and claim a few trends and outlook for the future developments.

2. Basic Descriptions of Laser Cooling

First of all, before going to explain the details of laser cooling, one should understand some basic concepts of this theory. The term 'laser cooling' is frequently used to describe the cooling and trapping of atoms and ions to reach the very low temperatures. The term 'Temperature' refers to the measurement of the average kinetic energy, which can also be described as momentum, of atoms in a physical system that has reach to the state of balance. When cooling the atom, the momentum of the atom is reduced by the interaction of atomic transitions shifted by Doppler with cross-propagation laser beams [5]. Obviously a coherent optical field that has been tuned creates an effective optical drag, which efficiently slow the velocity of the atoms to very low temperatures, which are 1 μK or lower [6]. As for the laser, the full name of it is light amplification by stimulated emission of radiation, so that the laser beam that used in the laser cooling is coherent light, which contain many photons that have a very narrow frequencies and well defined phase polarization and propagation direction. A monochromatic light wave of frequency v consists of massless particles, called photons, of energy E = hv, the constant h means Planck's constant. Photons move at the light's velocity c, with momentum p = E/c. As it known to all, the atom can only have certain fixed energies, and the energy is quantised, so that the atom can exist only in certain discrete energy levels. The discrete energy states are associated with the orbits of electrons in an atom, as shown in Fig. 1. Therefore, only certain photon energies are allow when electrons jump down from higher levels to lower levels. When the electrons jump down from the higer level E_2 to the lower level E_1, the atom will release photons with the certain frequency v, and it is associated with the two level.

$$hv=E_2 - E_1. \quad (1)$$

Laser cooling shows how atoms could reach thermal equilibrium by exchanging the energy and momentum with photons.

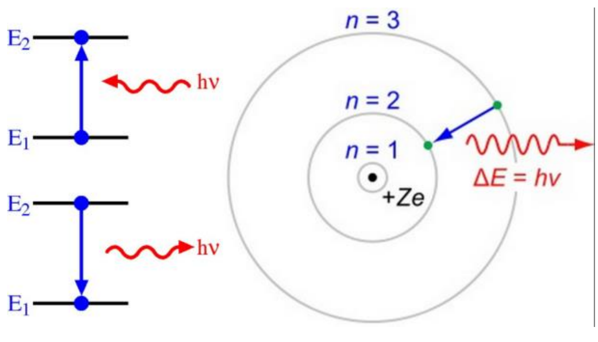

Figure 1. Discrete energy levels and the orbits of electrons in atom

3. Principle of Laser Cooling

Lasers are used to cool atoms and molecules by exploiting the doppler shift that is associated with the translational momentum. The atom moves toward the laser will see photon Doppler shifted onto the resonance and absorb the photon along with its momentum. The atoms can exist in the ground state or a higher state, which is call the excited state, and the transition between these two states has an angular frequency ω_0. The excited state can only maintain a short time τ. There is a natural linewidth that corresponds to the transition T=1/τ. One knows that T is much shorter compared to ω_0, and typically $T \sim 10^{-8}\omega_0$ [7]. It is obvious that the excited state is instable, and it will quickly decay to the ground state. During this process, the atom has spontaneous emission, but this emission is random and the direction of it is absolutely uncertain. Therefore, one can use this mechanism to slow down the velocity of the atom as illustrated in Fig. 2. Researchers use the laser beam with the certain frequency moves toward the atom, and then the atom absorbs the photon and the momentum of the photon. The atom in the ground state can be excited by absorbing a photon in the certain frequency, and it is probable that the laser beam is directed in the opposite direction of the motion, as the light is Doppler-shifted towards resonance. The momentum of this photon which has been absorbed, is transferred to the atom, and reduces its velocity by hv/cm, where m is the mass of the atom. The atom in the excited state will qucikly decay back to the ground state, which is due to the spontaneous emission. During this process, the photon that the atom emits, is going away in the random direction. This sequence is characterized by prior absorption from the laser beam that opposes to the movement, followed by the spontaneous emission that is randomly directed, and this process keep repeating until the velocity of the atom becomes very close to zero [7].

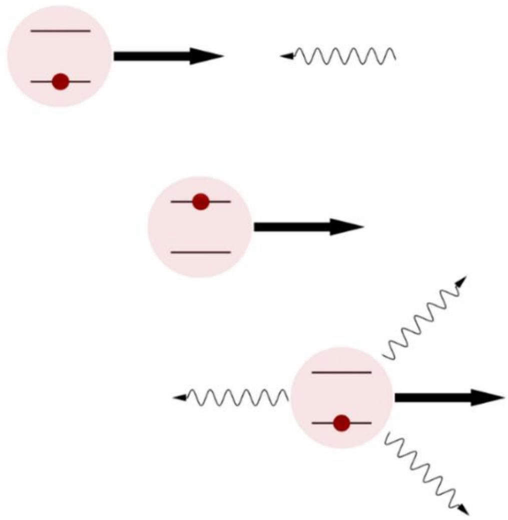

Figure 2. Principle of laser cooling

4. Principle of Laser Trapping

The idea that a photon has momentum and the light has the capability to exert pressure on electrically objects has been around for a while, starting with Kepler and Newton. That brilliant idea was eventually confirmed by Maxwell. Maxwell discovered that the momentum was small, suggesting that the small forces caused by light being absorbed or reflected by macroscopic objects are small. In fact, it was only after the turn of the century, when all the prerequisites are ready, for example the mirrors were suspended on fine torsion fibers and the experiments were conducted with the invention of the high-vacuum pump, by eliminating thermal or radiometric forces, researchers finally have the capability to detect the weak forces from the light reflection, which is identical with the Maxwell's theory [8].

Laser trapping is also called optical tweezer, because it can catch the particle and trap it in the certain room. When light goes through the particle, because of the reflection, the path of the light has changed. Although the photon is massless, but it still carries momentum. Therefore, though F=ma is not suitable for the massless photon, one can still consider that there exists a force that change the momentum of the photon, and on the opposite, there is a reaction force on the particle (seen from Fig. 3).

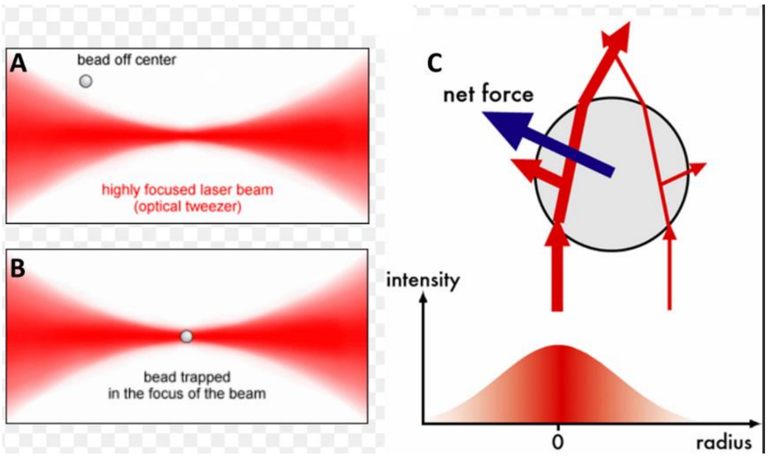

Figure 3. Principle of Laser Trapping

As it known to all that the light can add the force to the particle, lasering trapping become possible, by using the laser radiation pressure. Experiments with translucent spheres which are micrometer size in liquids first demonstrated that the light force is turely existed, which have a high viscosity and the gravity also plays a improtant role in the experiments. The light makes the spheres slide along the laser beams, and the velocities are proportional to radius. Stable laser trapping of individual particles were first found at the experiment that spheres located in the liquids was shaped by a pair of relative focused beams [8]. Laser trapping is also possible in the media which has less dense, for example air. In this atomsphere, the objects can tightly trap the particles against the gravitational force with a individual and vertically directed laser beam. In this case, one can slow down an atom by using the radiation pressure of a laser beam which has been tuned to the resonance of atom. After being slowed, the atom would be captured in a trap which is consisted of focused laser beams. During this process, the atomic momentum will be reduced until the atom's temperature finally reached the range of microkelvin [9].

The optical forces are resulted from the exchange of momentum of laser light are easilly to give a strongly effect to the motions of small particles which range from the micrometer particles to the molecules or even atoms. This optical forces permit researchers to trap small particles in a small space, help them float against the gravity, and operate them all alone, combine them in many different pairs, selective an individual of them, and consider them as sensitive crafts in many different fields, such as optical measuring, magnetic, radiometric, electric, viscous drag, and even gravity forces [10]. The optical trap is consisted of a laser beam which has been focused and an objective lens. A dielectric particle close to the focus will suffer a force that generate by the transfer of the momentum from the incident photons' scattering. In this case, the optical force can be seperated into two parts: (1) a scattering force, which is along the light propagation and (2) a gradient force, which is in the direction of the gradient of the spatial light. When a laser is being focused by the objective lens to its diffraction limit, it is possible to trap the small particles in 3-dimensions at the focus. What's more, due to the difference of the diameter of the particles and the wavelength of the laser beam, there are two different mechanisms of the laser trapping, when the diameter of the particle is bigger than the laser's wavelength, the laser beam acts like force. On the opposite, the optical tweezer acts in the electromagnetic model, the particle is attracted to the mid due to the potential of optical tweezer.

The first magnetic trapping of the atoms which has used a pair of superconducting in a cell. After that, there are many other experiments that have invented the magnetic trapping of cooling atoms on the very low temperatures such as 100 mK or even lower [10]. Now, adding the laser trapping with the magnetic trapping, one can cool down the temperature to lower point, and it is much easier to manipulate the particle in the microscale.

5. Comparison and Application

Laser cooling is used to slow down and cool the atoms and molecules, and it is widely used in many field. Recently, researchers have invented other systems of condensed matter with an emphasis on semiconductors by laser cooling. Semiconductor coolers can afford much more efficient pump of the light absorption, which has the potential to reach the lower temperatures, and the opportunity to make the electronic devices and photonic devices become incorporation. Nevertheless, these materials meet their own challenges in the application of the engineering, and there is no final cooling has been invented right now. The biggest difference between semiconductors and the materials is their cycle system about cooling [11]. Laser trapping is invented base on the theory of radiation pressure. Today, there are many groups can cool molecules to cold or ultra-low temperatures by exploiting the 3D magneto-optic traps. Recently, these groups has focussed on the ultra-low temperature molecules' transferring into traps for the study in the future [12]. With the applications of these three cross-orthogonal pairs of laser beams in the opposite directions, the atoms' movement in the overlap can be well controlled in all 3-D, therefore, the collection and cooling down of atoms can be finished in a little room [13]. Besides, the optical trapping has been widely use to manipulate the object in microscale, such as cell and bacteria. What's more, researchers can use optical trap to do precise experiment to find out the detail of many atoms and molecules. Optical trap is really a excellent tool in the research in the quantum mechanics, which can slow down the movement of the atom to look careful on the structure and rule for this area.

6. Limitations and Future outlooks

Although it seem that laser cooling can slow down the velocity of atom and reach the Bose-Einstein condensate, there are still many issues exist. If there are no other influence, such as outside absorption, all the atoms would quickly reduce the velocity to zero, and this means that the temperature would reach 0 K, a ridiculous result, which will never happen in the real world. In the laser cooling, the forces will become bigger due to the momentum's exchange between atoms and photons. This transfer makes up a heated mechanism that should be considered in the process of laser cooling. When the momentum of the atoms changes, the kinetic energy changes on an average by at least the retroacion energy. This explaination states that each absorption has an average frequency. In the similar situation, the energy produced by each spontaneous decay must be decomposed to the photon's outgoing energy and the atom's kinetic energy. Thus, the loss in the light field has an average energy, and it is suitable for every scattering event. This loss happens at the rate of twice the frequence of the laser beam, and the energy is converted to the kinetic energy of atoms, which is resulted from the atoms' reaction from every individual event. As a result, the atom is warmed because the backlash happen in the every directions [13]. Therefore, with the laser cooling, one can not reach such a low temperature as Bose-Einstein condensate.

However, using laser cooling with evaporative cooling, get very cold gases of atom in an optical and magnetic trap. Although now it is not the real Bose-Einstein condensate, with the development of the technology, one will reach it one day in the future. Lasering trapping or optical tweezer, it has been used in the experiment in three-dimensional optical molasses. Even though the atoms were gathered and slowed down in the overlap region, it is obviously that the optical molasses are still not becomed a absolute trap. The atoms which go away do not suffer any force to direct them coming back. These atoms can spread freely in different directions and even can escape from the trap, if only there is sufficient time for the diffuse movement to finally permit them to go to the farthest place of the overlap of the laser cone [13].

7. Conclusion

To sum up, this study introduced some basic concepts of atomic motion, and explain the principle of the laser cooling and the laser trapping. This report shows the analysis of the principle and new applications for laser cooling and trapping, and also makes a comparison between these two techniques. Besides, the limitations of laser cooling and trapping have been pointed out and the future development has been discussed. These results offer a guideline for having a better understanding of laser cooling and trapping, and knowing the limitations of them.

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