International Journal of Science and Research (IJSR)
ISSN: 2319-7064
SJIF (2022): 7.942

Advancements in Laser Cooling and Magnetic Trapping Techniques

G. S. Mendhe

Department of Physics, Adarsha Science, J. B. Arts and Birla Commerce Mahavidyalaya, Dhamangaon rly, Dist: Amravati, Maharashtra, India
Email: *girish24mendhe[at]gmail.com*

Abstract: ***The ability to cool, manipulate, and trap atoms using laser light has allowed a new, fast developing field to emerge. The term "laser cooling" describes a variety of methods that use one or more laser light fields to interact with atoms and molecules to cool them down to almost absolute zero.The review paper explores the advancements in laser cooling and magnetic trapping methods, focusing on their applications in achieving ultra-cold temperatures for atoms. It discussed various techniques such as Doppler cooling, optical molasses and evaporative cooling, highlighting their roles in advancing atomic clock accuracy and quantum degeneracy research.. The paper emphasizes the importance of these methods in achieving temperatures in the nano-kelvin range without cryogenic methods, marking a significant leap in atomic manipulation and study.***

Keywords: Laser cooling, Doppler cooling, Optical molasses, Evaporative cooling

1. Introduction

Electromagnetic interactions can be used to act on atoms, to manipulate them, to control their various degrees of freedom. In recent years, this scientific field has significantly grown with the development of laser sources, enabling substantial reduction in atomic speed through optical control. The field has been called laser cooling as the dispersion of atoms in a sample is exactly proportional to its temperature, and this moniker has stuck throughout time. Laser cooling describes the cooling of a physical system (atoms, ions, or solids) upon interaction with laser light. Laser-cooled atoms will undoubtedly make spectroscopic observations easier in the future, which could result in significant advancements in areas like atomic clocks and fundamental constant measurements. Cooling and trapping will enable researchers to examineatom-to-atom collisions in more detail and gain a better understanding of how chemical bonds are formed. The recent advances have led to realization of the dream of physicists of confining the atoms and reducing their velocities to the limit imposed by quantum mechanics. The cooled and trapped atoms and ions could be used for a variety of novel studies that could help with a wide range of theoretical physics issues.

Ashkin observed significant scattering of atoms by laser light and proposed their potential trapping by this force [1]. In 1975, T. W. Hansch and A. L. Schawlow proposed the first technique of laser cooling. In this paper, the impact of radiation pressure on any light-reflecting material is described. That concept was then connected to the cooling of atoms in a gas [2]. In 1978, Ashkin described how radiation forces can be used to simultaneously cool and trap atoms. He highlighted how this method would enable extended spectroscopic observations without the atoms escape the trap and suggested that optical traps be overlapped to investigate atom-to-atom interactions [3]. For electric dipole transitions, the Doppler cooling limit is usually in the hundreds of microkelvins. This threshold was thought to be the lowest temperature possible in the 1980s. It was a surprise then, when sodium atoms were cooled to 43 microkelvin when their Doppler Cooling limit is 240 microkelvin [4]. In 1982, William Philips applied the same principles to laser cool neutral atoms. In 1982, he published the first paper where neutral atoms were laser cooled [5]. Steven Chu, Claude Cohen-Tannoudji and William D. Philips succeeded in cooling and trapping atoms with laser light and were awarded in 1997 the Nobel Prize in Physics for their work [6]. In 1995 Cornell, Wieman and their colleagues succeeded for the first time in cooling a dilute gas of rubidium atoms (Rb^{87}) to nanokelvin temperatures [7]. They were awarded the Nobel prize in Physics in the year 2001 for this work.

The purpose of this review is to explore recent advancements in laser cooling and magnetic trapping techniques, highlighting their implications in modern Physics and potential applications in various fields. The significance of this review lies in its comprehensive coverage of the latest developments in laser cooling and trapping methods, which are crucial for advancing our understanding of atomic behavior and quantum phenomenon.

2. Different Methods of Laser Cooling

2.1 Doppler Cooling

The principle of Doppler cooling has been suggested by T.W. Hansch and A.L. Schawlow [2] for neutral atoms, and by D. Wineland and H. Dehmelt [8] for trapped ions.Any ray of light falling on matter exerts pressure. If the photon falls on an atom which has a resonance frequency equal to that of the photon, the atom absorbs the photon. If two particles with different momenta coming from opposite directions collide and after the collision the second particle is absorbed by the first then from the law of conservation of momentum, the momentum of the second particle is transferred to the first and consequently the first particle is decelerated. Similarly, if an atom resonantly absorbs a photon coming from the opposite direction, the momentum of the photon is transferred to the atom and the atom is pushed back and loses its velocity. If the photon and atom moving in a same direction, the atom may be accelerated in the same process. In order to ensure the deceleration of the atom, the atom should absorb only the oppositely moving radiation. This is achieved by using Doppler effect. The radiation frequency is detuned to lower than the resonant frequency so that due to Doppler effect, the atom will see the higher frequency for the oppositely moving radiation and move closer to the resonance. But it will see a lower frequency of the wave if it is coming from the same direction and will go away from resonance. Hence the possibility of the absorbing the oppositely moving radiation is larger. If there are two counter propagating waves they can be used to decelerate the atoms coming from both the directions [2]. After the absorption, the atom emits photons which may also accelerate them. But the spontaneous emission is a random process, so the net change of momentum is zero. But the energy change in a recoil process does not average to zero and may cause heating. This leads to a lower limit of cooling [9]. Thus the process of Doppler cooling can lower the temperature to the order of 100 μK for alkali atoms.

2.2 Optical Molasses:

With the help of three mutually perpendicular laser beams one can produce cooling in all six dimensions by reflecting each beam by a mirror. This is called optical molasses since the atoms experiences a strong viscous force in the three dimensional space [10]. When a fly falls in a pot of molasses it struggles to get out of a pot of molasses. Molasses pushes the fly in the opposite direction of whichever direction it tries to go in. The poor fly is unable to escape. An atom in an optical molasses faces a similar condition, however, if the atom can escape the molasses, its inertia will cause it to travel at the residual velocity. So, one has to find a method to hold them once they are in optical molasses. This is achieved by using magnetic field [11]. It was found by Phillips and coworkers that the optical molasses could produce a temperature much lower than the Doppler cooling limit [4].

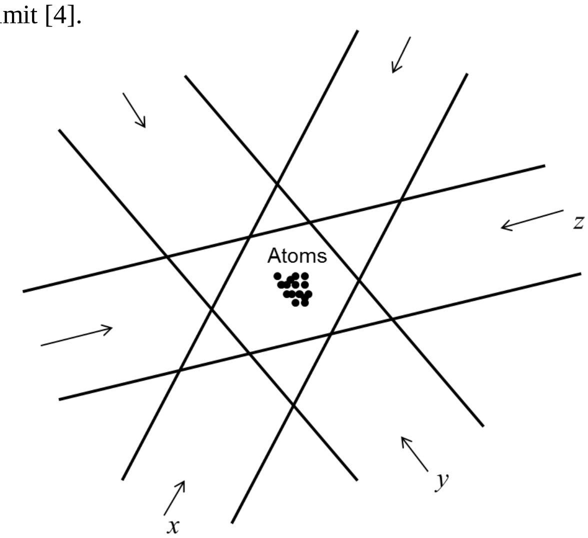

Figure 1: Optical Molasses

2.3Sisyphus Cooling

Cooling below the Doppler limit was explained by Dalibard and Cohen – Tanoudji in 1989 [12]. They showed that a combination of three known effects optical pumping, laser polarization gradient and light shifts could produce such low temperature. In optical molasses the atoms are made to climb up energy hills. When the atoms climb up to the top of the energy hills they fall down to the energy valley due to optical pumping and have to climb up again. Sisyphus of Greek mythology had to face an ever climbing hill with a ball. He never had a chance to climb down. The energy valleys are produced in the space coordinate by the laser polarization gradient produced by the counter propagating laser beams, optical pumping and light induced shift of energy levels. The atoms face an ever climbing hill and have no chance to go down the energy hill. Whenever the atoms climb up the hills, it has to do some work; thus it losses energy and gets cooled. The temperature of the order of μK could be reached for the alkali atoms in this process.

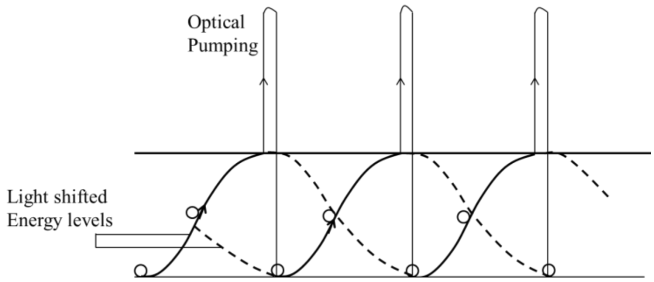

Figure 2: Sisyphus Cooling

2.4Magneto optical Trap:

Once the atoms are cooled to μK range of temperature, we have to confine them. If the cooling laser is turned off the atom will start moving apart with their residual velocities and will hit the walls or eventually fall down under gravity. The cold atoms usually have a velocity of a few cm/s. Hence a relatively weak magnetic field may be used to confine them. Alkali atoms have a magnetic moment because they have an unpaired electron. The magnetic moment is in a direction opposite to that of the electron spin. The magnetic moment interacts with an applied weak magnetic field. If the magnetic moment is parallel to the external magnetic field the atom is attracted to the local minimum of the field and trapped. Thus the magnetic field can act as a little bowl and the atoms can be trapped in the bowl [11].

2.5Evaporative cooling:

It was shown by Hess that the idea of evaporative cooling could be applied to the atoms confined in a magnetic bowl [13]. In this case we have to take the higher energy atoms out of the bowl so that the rest will be colder. Atoms are first cooled and trapped in the magneto-optical trap (MOT) By using optical pumping all the atoms can be brought to the same spin state (spin up say) because of the polarization dependent selection rule between the spin states. The atoms are then attracted to the local minimum. If the radio-frequency oscillating field is applied to the induce transitions in the atom between the spin up state (attracted to the magnetic trap) and the spin down state (repelled by the magnetic trap) the atoms will undergo a spin – flip transition. If the RF field is tuned to the higher energy side of the magnetic bowl the atoms having higher energy will first jump the well and will fall out of the bowl. When the atoms from the top of the bowl are removed the radiofrequency can be lowered to get deeper in to the atomic cloud in the bowl and this will induce more atoms to leave the bowl. The remaining atoms get colder in the process. When the large numbers of atoms are expelled from the barrier the barrier potential also gets modified. The process is discontinued when the temperature goes down to nearly 100 nK and only a few atoms are left to form condensate. This process of cooling is comparable with that in a cup of tea. When we take a sip the hotter tea molecules come out first. In a magnetic bowl, the RF field provides sucks the hotter atoms.

3. Conclusion

This review highlights significant advancements in laser cooling and magnetic trapping techniques. These methods have opened new frontiers in atomic physics, enabling researchers to cool atoms to nano-kelvin temperatures without cryogenics, thereby facilitating breakthroughs in quantum mechanics and precision measurements. Future research in this field holds the promise of furthering our understanding of atomic behavior in extreme conditions.

References

[1] Ashkin, “Atomic-Beam Deflection by Resonance-Radiation Pressure” Phys. Rev. Lett. 25,pp. 1321-1324, 1970.
[2] T. W.Hansch, A. L.Schawlow, "Cooling of gases by laser radiation". Optics Communications, 13(1),pp. 68–69, 1975.
[3] Ashkin, "Trapping of Atoms by Resonance Radiation Pressure",Physical Review Letters. 40(12): pp. 729–732, 1978.
[4] Paul D. Lett, Richard N. Watts, Christoph I. Westbrook, William D. Phillips, A. Winnicki, Phillip L.Gould, Harold J. Metcalf, "Observation of Atoms Laser Cooled below the Doppler Limit",Physical Review Letters,61(2), pp. 169–172, 1988.
[5] William Phillips, "Laser Deceleration of an Atomic Beam",Physical Review Letters,48(9), pp. 596–599, 1982.
[6] William D. Phillips, "Nobel Lecture: Laser cooling and trapping of neutral atoms", Reviews of Modern Physics,70(3), pp. 721–741, 1998.
[7] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, “Observations of Bose Einstein condensation in a dilute atomic vapor”, Science 269, PP. 198-201, 1995.
[8] D. Wineland and H. Dehmelt, “Proposed 1014 delta upsilon less than upsilon laser fluorescence spectroscopy on t1+ mono-ion oscillator iii”Bulletin of the American Physical Society, Vol. 20, No. 4, pp637,1975.
[9] D. J. Wineland and W. M. Itano, “Laser Cooling of atoms”, Physical Review A,20 (4), pp 1521-1540, 1979.
[10] S. Chu, L. W. Hollberg, J. E. Bjorkholm, A. Cable and A. Ashkin, “Three-dimensional viscous confinement and cooling of atoms by resonance radiation pressure”,Physical review letters 55 (1), pp48, 1985.
[11] E.Raab, M. Prentiss, A. Cable, S. Chu and D. Pritchard, “Trapping of neutral sodium atoms with radiation pressure”, Physical review letters,59 (23), pp 2631, 1987.
[12] J.Dalibard and C. Cohen-Tanoudji, “Laser cooling below the Doppler limit by polarization gradients: simple theoretical models”, J. Op. Soc,. Am. B6 pp, 2023- 2045, 1989.
[13] H F Hess, “Evaporative cooling of magnetically trapped and compressed spin-polarized hydrogen”, Physical Review B, 34, pp 3476, 1986.