AASCIT Communications
Volume 3, Issue 3
ISSN: 2375-3803

American Association for Science and Technology

Ultra Cold Atoms Using Laser Light

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Received: February 14, 2016; **Accepted:** February 29, 2016; **Published:** March 14, 2016

Keywords

Doppler Effect, Exotic States, Quantum Computation, Quantum Simulation, Condensed Matter, Laser Cooling

The invention of the laser spurred the development of additional techniques to manipulate atoms with light. Using laser light to cool atoms was first proposed in 1975 by taking advantage of the Doppler Effect to make the radiation force on an atom dependent on its velocity, a technique known as Doppler cooling. One of the major technical challenges in Doppler cooling was increasing the amount of time an atom can interact with the laser light. Ultra cold atoms may even allow creating exotic states of matter, which cannot otherwise be observed in nature. Owing to their unique quantum properties and the great experimental control available in such systems, ultra cold atoms have a variety of applications, namely, quantum computation and quantum simulation in the context of condensed matter physics where it may provide valuable insights into the properties of interacting quantum systems. Laser cooling is primarily used to create ultra cold atoms for experiments in quantum physics.

Introduction

A brief mention about the Nobel prizes in the field related to optics: in 1997, for the development of methods to cool and trap atoms with laser light; in 2001, for the achievement of Bose–Einstein condensation in dilute gases of alkali atoms; in 2005, for contributions to the quantum theory of optical coherence and for the development of laser-based precision spectroscopy; in 2008, for the discovery and development of the green fluorescent protein; in 2009, for the CCD sensor and transmission of light via optical fibers; in 2012, for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems; and in 2014, for the invention of efficient blue light-emitting diodes (physics) and for the development of super-resolved fluorescence microscopy (chemistry) to name but a few of the more recent achievements.

Optical cooling and trapping technique is applied widely to objects ranging from neutral atoms and ions to nanostructures, dielectric particles, and biological specimens. It encompasses both fundamental studies, e.g., Bose–Einstein condensates, cold atom collisions and optomechanics, and applications to new kinds of physics measurements and processes such as high resolution spectroscopy, atomic clocks, biomolecular interactions, and atomic- and nano-scale fabrication. Research activities span the range from technical instrumentation to highly refined theoretical advances.

Ultra cold atoms are prepared through the interactions of a diffuse gas with a laser field. When light is irradiated on atoms evidence on radiation pressure has been demonstrated by Lebedev, and Nichols and Hull in 1901. Otto Frisch in 1933 has demonstrated the deflection of individual sodium particles by light generated from a sodium lamp. The invention of the laser spurred the development of additional techniques to manipulate atoms with light. Using laser light to cool atoms was first proposed in 1975 by taking advantage of the Doppler Effect to make the radiation force on an atom dependent on its velocity, a technique known as Doppler cooling. 'Optical molasses' is the name given to the Doppler cooling in three dimensions which will slow atoms to velocities that are typically a few cm/s. One of the major technical challenges in Doppler cooling was increasing the amount of time an atom can interact with the laser light. This problem was addressed by the introduction of a Zeeman Slower which uses a spatially varying magnetic field to maintain the relative energy spacing of the atomic transitions involved in Doppler cooling. This increases the amount of time the atom spends interacting with the laser light. The 1997 Nobel Prize in physics was awarded for development of methods to cool and trap atoms with laser light and was shared by Steven Chu, Claude Cohen-Tannoudji and William D. Phillips. In 1987, Raab et al, developed the first magneto-optical trap (MOT). Temperatures achieved with a MOT are tens to hundreds of microkelvin. A magneto optical trap confines atoms in space by applying a magnetic field so that lasers not only provide a velocity dependent force but also a spatially varying force. The other method is the 'evaporative cooling' method. Evaporative cooling was used in experimental efforts to reach lower temperatures in an effort to discover a new state of matter predicted by Satyendra Nath Bose and Albert Einstein known as a Bose-Einstein condensate. (BEC). A Bose–Einstein condensate (BEC) is a state of matter of a dilute gas of bosons cooled to temperatures very close to absolute zero(that is, very near 0 K or −273.15°C). Under such conditions, a large fraction of bosons occupy the lowest quantum state at which point macroscopic quantum phenomena become apparent. The Nobel Prize in 2001 was awarded to Eric A Cornell, Wolfgang Ketterle and Carl E Wieman for the achievement of (BEC) in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates. In evaporative cooling the hottest atoms in a sample are allowed to escape which reduces the average temperature of the sample. Ultra cold atoms are also used in experiments for precision measurements enabled by the low thermal noise and, in some cases, by exploiting quantum mechanics to exceed the standard quantum limit. Ultra cold atoms may even allow creating exotic states of matter, which cannot otherwise be observed in nature.

Magneto Optical Trap

A magneto-optical trap (MOT) is an apparatus that uses laser cooling with magneto-optical trapping in order to produce samples of cold, trapped, neutral atoms at temperatures as low as several microkelvins two or three times the recoil limit or Doppler cooling limit. The figure 1 below shows the magneto-optical trap.

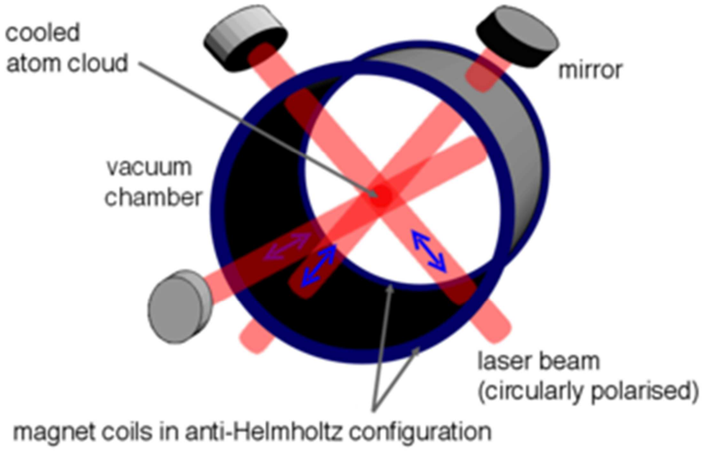

Figure 1. *Magneto Optical Trap (MOT). Courtesy: (Wikipedia).*

By combining the small momentum of a single photon with a velocity and spatially dependent absorption cross section and a large number of absorption-spontaneous emission cycles, atoms with initial velocities of hundreds of meters per second can be slowed to tens of centimeters per second. All magneto-optical traps require at least one trapping laser plus any necessary repumping laser. If the density of the MOT is high enough, the MOT cloud goes from having a Gaussian density distribution (left) in [Fig. 2] to something more exotic (right) [Fig. 2]. In the right hand image, the density is so high that atoms have been blown out of the central trapping region by radiation pressure, to then form a toroidal racetrack mode around it.

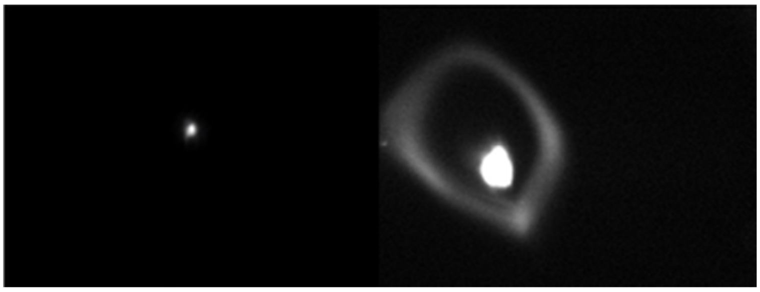

Figure 2. *MOT cloud in two different density regimes. (Courtesy: Wikipedia).*

Doppler Cooling

Photons have a momentum given by $\hbar k$ (where $\hbar$ is the reduced Planck constant and k the photon wave number), which is conserved in all atom-photon interactions. Thus, when an atom absorbs a photon, it is given a momentum kick in the direction of the photon before absorption. By detuning a laser beam to a frequency less than the resonant frequency (also known as red detuning), laser light is only absorbed if the light is 'frequency up-shifted' by the Doppler Effect, which occurs whenever the atom is moving towards the laser source. If the absorption and emission are repeated many times, the average speed, and therefore the kinetic energy of the atom will be reduced. Since the temperature of a group of atoms is a measure of the average random internal kinetic energy, this is equivalent to cooling the atoms. Other methods of laser cooling include: a) Sisyphus cooling) Raman sideband cooling) Resolved sideband cooling) Velocity selective coherent population trapping) Use of a Zeeman slower) electromagnetically induced transparency cooling and g) Cavity mediated cooling. Doppler cooling, as shown in [Fig. 1] above, is usually accompanied by a magnetic trapping force to give a magneto-optical trap is by far the most common method of laser cooling. It is used to cool low density gases down to the Doppler cooling limit. Doppler cooling is also used in spectroscopy and metrology, where cooling allows narrower spectroscopic features. For example, all of the best atomic clock technologies involve Doppler cooling at some point [1].

Laser Cooling

Laser cooling is primarily used to create ultra cold atoms for experiments in quantum physics, Fig 3, 4. These experiments are performed near absolute zero where unique quantum effects such as Bose-Einstein condensation can be observed. Laser cooling has primarily been used on atoms, but recent progress has been made toward laser cooling more complex systems. In 2010, a team at Yale successfully laser-cooled a diatomic molecule [2]. In 2007, an MIT team successfully laser-cooled a macro-scale (1 gram) object to 0.8 K. [3] In 2011, a team from the California Institute of Technology and the University of Vienna became the first to laser-cool a (10 µm x 1 µm) mechanical object to its quantum ground state[4].

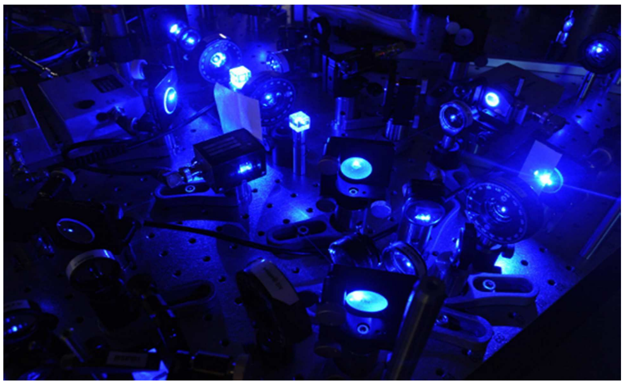

Figure 3. *Laser Cooling -Columbia University (Courtesy).*

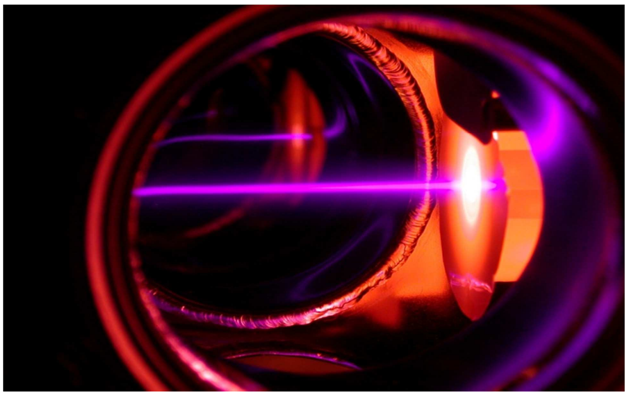

Figure 4. *Doppler laser cooling of atoms-Decoded Science-(Courtesy).*

Raman Cooling

Raman cooling is a cooling technique that allows the cooling of atoms using optical methods below the limitations of Doppler cooling. It is limited by the recoil energy of a photon given to an atom. This scheme can be performed in simple optical molasses which are known as free space Raman cooling [5] and Raman side-band cooling [6].

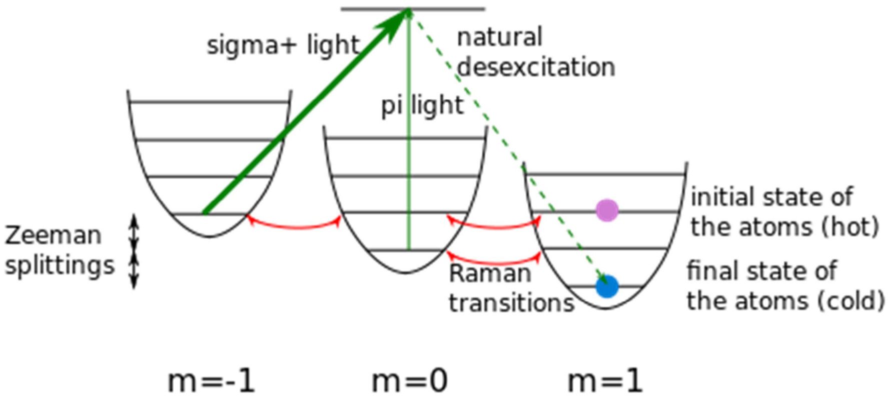

Figure 5. *Raman Side-band cooling -(Courtesy-Wikipedia).*

Both techniques make use of Raman Scattering of laser light by atoms.

Bell's Theorem

Bell derived in his seminal 1964 paper titled 'On the Einstein Podolsky Rosen paradox' [7], has been called, on the assumption that the theory is correct, "the most profound in science" [8].

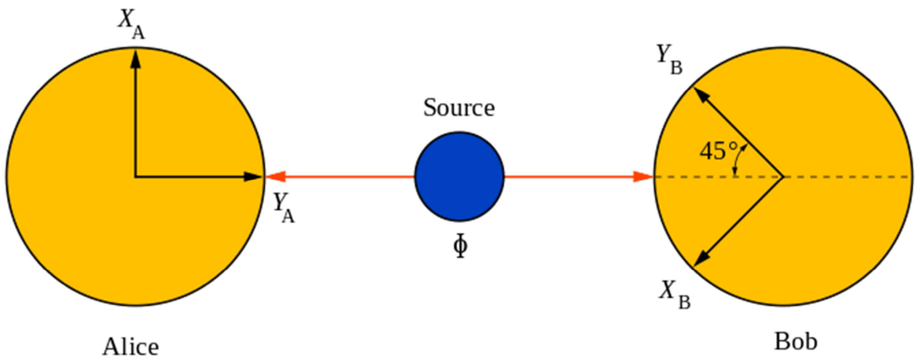

Figure 6. *Bell's theorem (Courtesy-Wikipedia).*

The title of Bell's seminal article refers to the 1935 paper by Einstein, Podolsky and Rosen [9] that challenged the completeness of quantum mechanics.

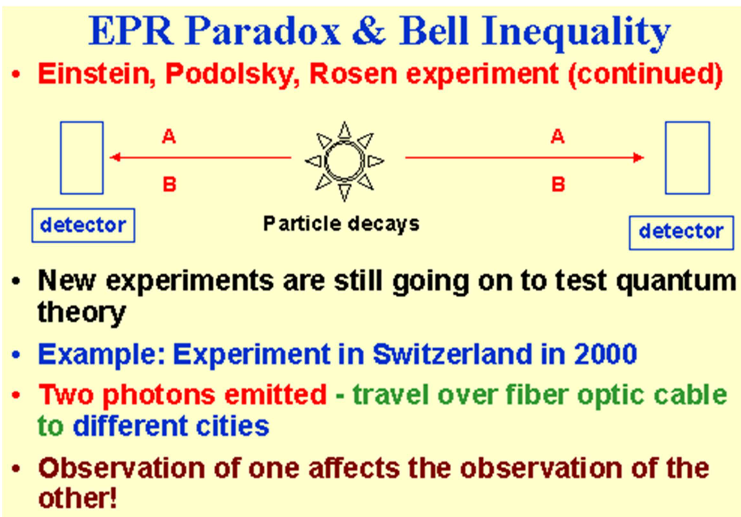

Figure 7. *EPR Paradox and Bell's Inequality-Courtesy-(Illinois University).*

In his paper, Bell started from the same two assumptions as did Einstein Podolsky and Rosen(EPR), namely (i) reality (that microscopic objects have real properties determining the outcomes of quantum mechanical measurements), and (ii) locality (that reality in one location is not influenced by measurements performed simultaneously at a distant location). Bell was able to derive from those two assumptions an important result, namely Bell's inequality. The theoretical (and later experimental) violation of this inequality implies that at least one of the two assumptions must be false.

Review of Various Research Works on Laser Cooling

A brief review of various research workers in the the field of laser cooling for nearly twenty years is taken up here. And surely is not considered as an exhaustive review work. Dalibard et al, [10], have worked on the basis of laser polarization gradients at low laser power, where the optical-pumping between different ground-state sublevels becomes long. Due to a large time lag between internal atomic response and the atomic motion, a large cooling force takes place. They also present two cooling mechanisms working below the Doppler limit. In the first method, the light shifts of the ground-state Zeeman sublevels are spatially modulated, and optical pumping among them leads to dipole forces and to a Sisyphus effect analogous to the one that occurs in stimulated molasses. In the second case ($\sigma^{+}-\sigma^{-}$ configuration), the cooling mechanism is radically different. Even at very low velocity, atomic motion produces a population difference among ground-state sublevels, which gives rise to unbalanced radiation pressures. They have used the semi classical optical Bloch equations and derive quantitative expressions for friction coefficients and velocity capture ranges. They have shown that the friction coefficients in both cases are independent of laser power that produces equilibrium temperature which is proportional to the laser power. Kosachiov D.V. etal, [11], have worked with laser cooling of three-level atoms in two standing waves. They have made use of the coherent population trapping because a sub-Doppler cooling requires equal detuning when the spatial phase-shift is zero. When two standing waves having spatial phases are different for different detuning, a sub-Doppler cooling will occur, which is very similar to the Sisyphus type of mechanism. Neither polarization nor a magnetic field is considered in this study. Metcalf H.J., et .al, [13], have given a wide review of various methods adapted in laser cooling and trapping of atoms. A review is presented of some of the principal techniques of laser cooling and trapping that have been developed during the past 20 years. Its approach is primarily experimental, but its quantitative descriptions are consistent in notation with most of the theoretical literature. It begins with a simplified introduction to optical forces on atoms, including both cooling and trapping. Then its three main sections discuss its three selected features, (1) quantization of atomic motion, (2) effects of the multilevel structure of atoms, and (3) the effects of polychromatic light. Blinov, B B [14], have used a radio frequency trap and have demonstrated the laser cooling of atomic ions. The temperature of a single ion is measured by observing the size of a time-averaged image of the ion in the known harmonic trap potential. Although the lowest observed temperature was only about 1K, this method efficiently cools very hot atoms and can sufficiently localize trapped atoms to produce near diffraction-limited atomic images.Toschek Peter.E. et al [15], have demonstrated novel variants of light caused by stimulated Raman type two-photon transitions combined with spontaneous Raman scattering. These efficient processes parallel the generation of a stimulated light force in a standing wave and the operation of a free-electron laser Nemova, Galina et.al [16], have presented a theoretical scheme for laser cooling with colloidal lead-salt PbSe quantum dots (QDs) doped in a glass host. The laser cooling process is based on the anti-Stokes fluorescence in QDs. Due to the short lifetime of the excited level of the PbSe Quantum Dot, the cooling process is accelerated and new materials with higher phonon energy are to be used as hosts, which are normally considered unsuitable for cooling with rare-earth ions. The increase in the absorption cross-section of the PbSe QD compared with absorption cross section of rare-earth ions doped in a glass host or in a crystal host increases the efficiency of the cooling process and also reduces the pump power requirements. Dong, Guang-Zong et. Al [17], have reported a theoretical scheme for laser cooling of solids based on energy transfer usually found in rare-earth co doped materials. The cooling scheme enables a large enhancement in the cooling efficiency with regard to the standard anti-Stokes fluorescence cooling. They have taken a Ho^{3+} and a Tm^{3+} co doped on a low-phonon crystal (LiYF4) sample and found that, initially, the cooling efficiency increases, and then decreases with the increasing of the resonant absorption. The optimal cooling efficiency is predicted to exceed 5%.The maximum cooling power density could be promoted greatly by applying the co doped cooling scheme. The cooling scheme is also suggested to be valid for other rare-earth (for example, Tm^{3+} and Er^{3+}, or Er^{3+} and Yb^{3+}) co doped materials. Wang, Xiaofeng et. al [18], have given a new approach to the design of Q-switched solid-state lasers that offsets heating loads by anti-Stokes fluorescence.

Some of the recent contributions are now discussed here below. Neves Antonio *et al.* [19] gives a very good introduction to optical cooling and trapping by various workers in this field. It describes, till date, all the latest technology adopted to cool and trap atoms. E.S de Lima Filho *et al.* [20] explore a new material for optical cooling. It is shown that ytterbium-doped glass ceramics shows the best measured cooling figures-of-merit of these samples, based on optical calorimetry because of the reduced non radiative decays. Bowman *et al.* [21] demonstrate the use of a spatial light modulator at several widely separated wavelengths to make tailored optical trapping potentials for use in ultra cold atom experiments. This method makes it possible to write different spatial patterns for each of the different wavelengths which then overlap in a certain restricted region of the Fourier plane. This technique has the potential to be used to generate optical potentials for neutral atoms with sub-diffraction limited spatial features. Glover and Bastin [22] investigate the use of spectrally broadened laser light for cooling and collimating an atomic beam. Ivanov *et al.* [23] present a new mechanism of laser cooling of crystals doped with rare-earth ions. The mechanism involves cooling cycles including two-photon Raman scattering through the dipole-allowed 5d ion level, electron-phonon transitions between the Stark split sublevels, and fluorescence from the excited ion level. Eerkens *et al.* [24] discuss a room temperature measurement of sideband cooling a mechanical object with a 10−10 kg mass, which is a bit more massive than those that have been sideband cooled. The frequency of the resonator is a few times less than a MHz, compared to MHz mechanical objects that have been cooled previously. By using high-quality Bragg mirrors, they construct a cavity and show its operation in the sideband resolved regime. Ground-state cooling and quantum superposition of such a macroscopic opto-mechanical system will appear within reach.

Conclusion

The year 2015 is significant for many reasons, including marking 20 years since the first realization of an atomic Bose–Einstein condensate, 45 years since the invention of optical trapping, the centennial of Einstein's theory of general relativity, 150 years since Maxwell's theory of electromagnetic waves, 200 years since Fresnel's proposition of the wave nature of light, and 1000 years since Ibn al-Haytham's treatise on Optics. It has been established by now, that laser cooling is a very powerful method to study properties of atoms and ions. Atoms in a thermal beam can be cooled, decelerated, and stopped using the radiation pressure from a nearly resonant laser beam. Several groups have already used this laser-cooling process. The techniques and results of the various experimental groups are reviewed, and applications of laser-cooled atoms, are increasing by the day.

Acknowledgements

The author is thankful to Prof. Dr. C. V. Jayakumar, Principal, Sri Sairam Engineering Colleg, Chennai, India and the management of the college, for encouraging research work and to publish the work in international journals of repute. ■

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Dr. T. K. Subramaniam earned his doctorate degree from the Banaras Hindu University, India, specializing in the field of laser spectroscopy. He has over twenty years of college level under-Graduate teaching experience in engineering physics and basic physics and a co-author on an engineering text book for the students. He also has specialized in experimental laser spectroscopy and has several papers in international journals of repute. Besides six years of industrial experience, he has also been an anonymous Peer-Reviewer for journals belonging to the Optical Society of America (OSA). Presently, he works as a Professor of Physics at Sri Sairam Engineering College, Chennai, India.
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References

[1] Phillips, W. D. (1997). "Laser Cooling and Trapping of Atoms" (PDF). *Nobel Lecture*. Nobel Foundation, pp. 199–237.

[2] E. S. Shuman, J. F. Barry, and D. DeMille (2010). "Laser cooling of a diatomic molecule". Science 467: 820–823. Doi: 10.1038/nature09443

[3] Massachusetts Institute of Technology (2007, April 8). Laser-cooling Brings Large Object near Absolute Zero. Science Daily. Retrieved January 14, 2011.

[4] Caltech Team Uses Laser Light to Cool Object to Quantum Ground State. Caltech.edu. Retrieved June 27, 2013. Updated 10/05/2011.

[5] Mark Kasevich, Steven Chu, "Laser cooling below photon recoil with three-level atoms", Phys. Rev. Lett. 69, 1741 (1992)

[6] Andrew J. Kerman, Vladan Vuletic, Cheng Chin, and Steven Chu, Beyond Optical Molasses: 3D Raman Sideband Cooling of Atomic Cesium to High Phase-Space Density, Phys. Rev. Lett. 84, 439 (2000).

[7] Bell, John (1964). "On the Einstein Podolsky Rosen Paradox" (PDF). Physics1 (3): 195–200.

[8] Griffiths, David J. Introduction to Quantum Mechanics (2nd ed.). Pearson/Prentice Hall p. 423, 1998.

[9] Stapp, Henry P. (1975). "Bell's Theorem and World Process". Nuovo Cimento29B (2): 270–276. Bibcode: 1975NCimB.29.270S. doi: 10.1007/BF02728310. (Quote on p. 271).

[10] Dalibard, J; Cohen-Tannoudji, C, "Laser cooling below the Doppler limit by polarization gradients: simple theoretical models, J. Opt. Soc. Am. B 6(11) 2023-2045 (1989).

[11] Kosachiov, D V; Rozhdestvensky, Yu V; Nienhuis, G, "Laser cooling of three-level atoms in two standing waves", J. Opt. Soc. Am. B 14(3) 535-543 (1997).

[12] Kaiser, Robin; Kastberg, Anders; Morigi, Giovanna, "Laser Cooling of Matter", J. Opt. Soc. Am. B 20(5) 883-883 (2003).

[13] Metcalf, H J; van der Straten, P, "Laser cooling and trapping of atoms", J. Opt. Soc. Am. B 20(5) 887-908 (2003).

[14] Blinov, B B; Kohn Jr , R N; Madsen, M J; Maunz, P; Moehring, D L; Monroe, C, "Broadband laser cooling of trapped atoms with ultrafast pulses", J. Opt. Soc. Am. B 23(6) 1170-1173 (2006).

[15] Toschek, Peter E; Neuhauser, Werner, "Optical cooling revisited", J. Opt. Soc. Am. B 6(11) 2220-2226 (1989).

[16] Nemova, Galina; Kashyap, Raman, "Laser cooling with PbSe colloidal quantum dots", J. Opt. Soc. Am. B 29(4) 676-682 (2012).

[17] Dong, Guang-Zong; Zhang, Xin-Lu; Li, Li, "Energy transfer enhanced laser cooling in Ho^{3+} and Tm^{3+}-codoped lithium yttrium fluoride", J. Opt. Soc. Am. B 30(4) 939-944 (2013).

[18] Wang, Xiaofeng; Cao, Dingxiang; Zhou, Mu; Tan, Jichun, "Q-switched lasers with optical cooling", J. Opt. Soc. Am. B 24(9) 2213-2217 (2007).

[19] Neves, Antonio A. R; Jones, Philip H; Luo, Le; Marago, Onofrio M, "Optical cooling and trapping: introduction" J. Opt. Soc. Am. B 32(5) Oct1 –Oct5(2015).

[20] E. S. de Lima Filho, K. V. Krishnaiah, Y. Ledemi, Y.-J. Yu, Y. Messaddeq, G. Nemova, and R. Kashyap, "Ytterbium-doped glass-ceramics for optical refrigeration," Opt. Express 23, 4630–4640 (2015).

[21] D. Bowman, P. Ireland, G. D. Bruce, and D. Cassettari, "Multi-wavelength holography with a single spatial light modulator for ultra cold atom experiments," Opt. Express 23, 8365–8372 (2015).

[22] R. D. Glover and T. Bastin, "Optical collimation of an atomic beam using a white light molasses," J. Opt. Soc. Am. B 32, B1–B10 (2015).

[23] A. Ivanov, Y. Rozhdestvensky, and E. Perlin, "Coherent pumping for fast laser cooling of doped crystals," J. Opt. Soc. Am. B 32, B47–B54 (2015).

[24] H. J. Eerkens, F. M. Buters, M. J. Weaver, B. Pepper, G. Welker, K. Heeck, P. Sonin, S. de Man, and D. Bouwmeester, "Optical side-band cooling of a low frequency optomechanical system," Opt. Express 23, 8014–8020 (2015).