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Laser Cooling Conditions Dependent on the Photon Density and Frequency Using Quantum Model based on Fluid Laws and Treating Atoms as Strings

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Abstract

Using the laws of fluid mechanics for gases and treating atoms as vibrating strings subjected to gas and photon pressure, a useful expressions for cooling conditions was found. These conditions can be applied to nano and quantum systems as far as the model recognises the particle dual nature, which is the cornerstone of quantum physics. These expressions indicated that the atoms density and the degree of cooling, as well the photon density and frequency, affected the cooling process. Dense and high cooling degree requires increasing the applied photon density or the frequency or both.

Keywords: cooling, atoms, photon, density, frequency, quantum, nano

Introduction

Laser is one of the most importance applications in our day life. It is s single wave length, very narrow beam, powerful intensive light [1]. Laser can be generated due to the so called stimulated emission of radiation . When a photon having energy equal to the energy difference between the ground and excited states is incident in an atom, it forces the electron in the excited state to return back to the ground state emitting a photon having the same frequency, direction and phase of the incident photon [2] . The two photons when incident on two excited atoms force them to emit two additional coherent photons .This amplifiction process continues till larger number of coherent photons emerge in the form of a highly very narrow powerful beam known as laser [3]. Laser is used in modern technology bin a wide variety of applications such as computer optical fibers in industry and medicine [4].

Recently laser cooling representsnone one of the importance industrial applications for superconductors that can be used in improving the performance of magnetic resonance imaging devives. Cooling can also be utilized to generate powerful magnetic field which in turn can generate powerful electric energy [5,6,7]. The cooling process requires slowing the atoms and molecules motion ,and decreasing their velocites , using photon pressure. According to the kinetic theory of gases the decrease of velocity decreases the temperature [8,9,10].

Ordinary laser cooling is based on the mechanical effect of single-photon transitions between ground states and electronically excited states.

One can also use multiple laser wavelengths and multiple atomic transitions for laser cooling and atoms traping by quantum optics tool. Traditional laser cooling relies largely on mechanical forces due to light scattering from a single frequency laser. Multiple wavelengths and transitions can lead to usual "single-photon" cooling: access to substantially different effective photon momenta, access to different atomic line widths and saturation intensities, the possibility of coherence and EIT effects, and the possibility to easily separate atom fluorescence from laser excitation by the three-laser excitation. Such technique is based on mechanical forces arising from excited state to excited state transitions. For example, replacing the single laser excitation by the three-laser excitation can lead to larger light scattering forces, and the fluorescence would be at a very different wavelength from the excitation lasers, which could be easily filtered away. Many attepts were made for laser cooling conditions. The laser cooling of a cryogenic buffer-gas beam of calcium monohydride (CaH) molecules was investigated. The vibrational branching ratios for laser cooling transitions for both excited electronic states *A* and *B were also determined* The repeated photon scattering via the $A \rightarrow X$ transition is found to be achievable at a rate of $\sim 1.6 \times 10^6$ photons s^{-1} l. A sub-Doppler cooling technique, namely the magnetically assisted Sisyphus effect, and use it to cool the transverse temperature of a molecular beam of CaH were also determined .Using a standing wave of light, the transverse temperature was lowered from 12.2(1.2) mK to 5.7(1.1) mK. This gives a clear pathway for creating a magneto-optical trap (MOT) of CaH molecules. Suchy a MOT could serve as a starting point for production of ultracold hydrogen gas via dissociation of a trapped CaH cloud [10] to an equal split of the cooling light into two fibers (1) and (2). This work study theoretically laser cooling feasibility of the molecule LuF, in the fine structure level of approximation. An ab-initio complete active space self-consistent field (CASSCF)/ MRCI with

Davidson correction calculation has been done in the $\Lambda^{(\pm)}$ and $\Omega^{(\pm)}$ representations. The corresponding adiabatic potential energy curves and spectroscopic parameters have been investigated for the low-lying electronic states. The results of the internuclear distances of the $X^3\Sigma_{0+}$ and $(1)^3\Pi_{0+}$ states show the candidacy of the molecule LuF for direct laser cooling$_+$. Franck– Condon factors, the radiative lifetimes, the total branching ratio, the slowing distance, and the laser cooling scheme study prove that the molecule LuF is a good candidate for Doppler laser cooling [11] . isotopes using gray molasses operating on their respective D_1 atomic transitions was investigated. For ^{7}Li the results show that the sub-Doppler cooling can be achieved with two distinct Λ-type transitions, where the upper level can be either of the two 2^2 $P_{1/2}$ hyperfine states. A temperatures of 85 μK, was obtained with atom numbers of 10^8, and phase-space densities in the range of 10^{-6} 10^{-5} for both isotopes. These conditions provide a good starting point for loading the mixture into an optical dipole trap and performing evaporative cooling to quantum degeneracy. This provides a valuable simplification for the preparation of ultracold ^{6}Li-^{7}Li mixtures, which were proven to be a successful system for the study of impurity physics and Bose-Fermi superfluids [12] Different other attepts were also done concerning laser cooling [13,14,15](4.3) Force for fluid and cooling conditions According to Newton second law the force F can be defined in terms of the mass M and the velocity v to be

$$F = \frac{dMv}{dt} \qquad (1)$$

The pressure is defined by

$$P = \frac{F}{A} \qquad (2)$$

For uniform velocity the force takes the form

$$F = v\,\frac{dM}{dt} \qquad (3)$$

But the fluid total mass M existing in a cylinder having area A and length x is given by

$$M = mN = mnAx \qquad (4)$$

Thus the force is given by

$$F = v\,\frac{dM}{dt} = v\,\frac{dnAxm}{dt} \qquad (5)$$

According to the definition of the velocity, one gets

$$F = vnAm\frac{dx}{dt} = v^2 nAm \qquad (6)$$

The pressure P is thus given for a photon of speed c and number density n by

$$P = \frac{F}{A} = v^2 nm = nmc^2 \qquad (7)$$

But for the photon having frequency f Plank hypothesis and special relativy gives the energy to be in the form

$$mc^2 = hf \qquad (8)$$

This means that the pressure exerted by the photon is given by

$$p_p = P = nhf \qquad (9)$$

Consider a stream of atoms moving in the positive x- direction with speed v and pressure p such that stream of photons moves in an opposite direction to excerted an inword pressure Pp on the a atoms . Therefore the fluid equation of motion for the particles with speed v is given by

$$\frac{dMv}{dt} = (\Delta p - \Delta Pp) \qquad (10)$$

Inost cases the medium atoms are in in the form of vibrating stings having variable non uniform velocity. Thus when no forces are excreted on them the atoms becomes at rest

$$O = (\Delta p - \Delta Pp) \qquad (11)$$

Thus the fluid pressure is equal to the photon pressure

$$P = p_p \qquad (12)$$

If the a toms have kinetic energies corresponding to thermal energy 1/2nakT . thus

$$P = \frac{1}{2}n_a mv^2 = \frac{1}{2}n_a kT \qquad (13)$$

Thus to stop a toms to cool them by laser to change its temperature from T to zero, the photon frequency and intensity n must satisfy equation (12) inserting (9) and (13) in (12) gives

$nhf = \frac{1}{2}$ nakT_1 (14)

To cool the same a toms density to from T1 and to O and from T_2 to 0 requires either changing the photons frequency or their density n or both. In general, cooling to O for T1 and T2 needs.

$N_1hf_1 = \frac{1}{2}$ nakT_1 (15)

$N_2hf_2 = \frac{1}{2}$ nakT_2 (15)

For photons of the same frequency equations (14) and (15) gives

$\frac{1}{2}$ nak (T_2 -T1)= ($n_2 - n_1$) hf = nhf

T_2 -T1=$\frac{2nhf}{nak}$ (16)

Thus to cool a toms from T_2 to T_1 one needs photons density and frequency to satisfy equations (15).

For photons having the same density but different frequencies (14) and (15) give

$\frac{1}{2}$ n_ak (T_2- T_1) = nh (f_2 - f_1)

Thus

$$T_2 - T_1 = \frac{2nh}{n_a k} (f_2 - f_1) \quad (17)$$

The requirement for cooling can be expressed in terms of laser intensity I and power. For laser having frequency f and density n , the power passing through area A is given by Pr = energy passing through area A per unit time (t = 1)

$(Total\ number\ of\ photone\ inside\ the\ cylinder\ emerging\ in\ one\ second)$× energy in one $photon$

= $photon\ density$ x $cylinder$ volume × hf

$$= n \times l \times Ahf = n \times c \times A \times hf$$

$$Pr = nhfcA \quad (18)$$

The intensity I is the power emerged per unit area

I = $\frac{Pr}{A}$ = nhfc (19)

According to equations (1o), (18) and (17) one can express the cooling conditions in terms of the laser intensity and power to get

$(T_2 - T_1) = \frac{2I}{h_a kc}$ (20)

Since the intensity and the power are related in terms of the area A by

I =Pr/A

Thus

$(T_2 - T_1) = \frac{2Pr}{h_a kA}$ (21)

However the situation is different for particles affected by a field having potential V. In this c ase equation (10)can be rewritten to be

$Type\ equation\ here.$

$$\frac{d(Mv)}{dt} = \Delta p - \Delta P_p - \Delta V$$

(22)

When the a toms becomes at rest the left hand side vanishes to get

$$O = (\Delta P - \Delta P_p - \Delta V) \quad (23)$$

This requires the zero colling condition to be

$$P_p = P - V \qquad (24)$$

In view of equations (4. 3. 9), (4. 3. 13) . one gets

$$nhf = \frac{1}{2}nakT - V \qquad (25)$$

To cool atoms from T_2 to zero and from T_1 zero , one gets

$$n_2hf_2 = \frac{1}{2}n_akT_2 - V$$

(26)

$$n_1hf_1 = \frac{1}{2}n_akT_1 - V \qquad (27)$$

For laser having the some frequency one gets

$$n_2hf = \frac{1}{2}n_akT_2 - V$$

$$n_1hf = \frac{1}{2}n_akT_1 - V \qquad (28)$$

Substracting the two relations gives

$$\frac{1}{2}n_ak(T_2 - T_1) = (n_2 - n_1)hf \qquad (29)$$

$$T_2 - T_1 = \frac{2nhf}{nak} \qquad (30)$$

Fortunately the cooling condition depends only on the properties of the laser only and dose not depend on the field permeated the medium. Assume now that atoms moving in the frictional medium, having frictional coefficient . ∝In this case equation (10) gives

$$\frac{dMv}{dt} = (\Delta p - \Delta p_p)A - \propto v \qquad (31)$$

For the atoms to be at rest, again the left hand side vanishes to get

$$O=\Delta(p - p_p)A - \propto v \qquad (32)$$

In are dimension

$$(P - P_p)A= \propto \int vdx = p_fA \qquad (33)$$

Where Pf stands for friction pressure

Therefore

$$p_f = P - P_p \qquad (34)$$

Hence

$$\frac{1}{2}n_akT = nhf + p_f \qquad (35)$$

Again the cooling condition requires

$$\frac{1}{2}n_akT_2 - \frac{1}{2}n_akT_1 = (n_2 - n_1)\,hf - p_f + p_f$$

$$T_2 - T_1 = \frac{2nhf}{n_ak} \qquad (36)$$

One can also assumes that when the temperature beam was applied thus the new temperature

Satisfies

$$\frac{1}{2}n_akT_2 - n_2hf = \frac{1}{2}n_akT_1 \qquad (37)$$

Again the cooling conditions depend on the laser properties only and are not affected by the medium friction

3.Discussion

The equation for a fluid depending on Newton second law was used to describe the behavior of atoms in the form of vibrating strings when laser photons having pressure Pp was applied on two opposite sides to appose the atoms pressure P which was treated as a gas. The model was put completly under the ambrella of quantum laws by recognizing the particle wave dual nature as shown in equation (1). Newton second law takes care of the particle nature, while string. solution secures the wave nature. The atoms can be cooled to rest according to this apprach when the photon pressure which depends on the photon density n and frequency f According to equation (9) equals the atoms pressure as shown in equation (12). The atoms pressure is temperature dependent according to equation (13) which is based on the kinetic theory of gases. Any gas can be cooled to zero from T1 by applying appropriate photon density and frequency. High temperature T1 and high density atoms na requires increasing either the photon density n or the frequency f or both. This agrees with experimental work and common sense. Equation (16) indicated that lowering temperature from T2 to T1 requires applying photons with density n frequency f or increasing the applied photon density by an amount n. The same results can be ground according to equation (17) but here the frequency needs to be increased. Equations (20) and (21) showed that increasing intensity and power of the photon causes more lowering to the gas temperature. Applying uniform potentialas shown in equation (22) and taking into account the effect of the friction as shown in equation (31) was shown in equations (29,30,36,37) gives the same results.

Conclusion

Based on a new quantum model recognising the wave particle dual nature,

useful expressions for cooling conditions was found for nano and quantum systems . These expressions showed that the atoms density and the degree of cooling beside the photon density and frequency affected the cooling process. Dense and high cooling degree requires increasing the applied photon density or the frequency or both.

References

1. Raymond A. Serway, *Physics for Scientists and Engineers with Modern Physics*, Sounders College Publishing, USA, 2004.
2. Paul G. Hewitt, John A. Suchocki, Leslie A. Hewitt, *Conceptual Physical Science* (5th Edition), Pearson, 2011.
3. Steven H. Simon, *The Oxford Solid State Basics*, Oxford University Press, USA, 2013, ISBN 978–0–19–968076–4.
4. Rohit P. Pavankumar, Antoinette J. Taylor, *Optical Techniques for Solid-State Materials Characterization*, Taylor & Francis Group LLC, New York, 2012.
5. M.A. Wahab, *Solid State Physics: Structure and Properties of Materials*, Alpha Science, 2005, pp. 1–3, ISBN 978-1-84265-218-3.
6. G. Aruldhas, *Quantum Mechanics*, PHI Private Limited, New Delhi, 2009.
7. David J. Griffiths, *Introduction to Quantum Mechanics*, Prentice Hall, New Jersey, 2005.
8. Hartmut Haug, Stephan W. Koch, *Quantum Theory of the Optical and Electronic Properties of Semiconductors* (5th Edition), Singapore, 2009, https://doi.org/10.1142/7184.
9. Lesley E. Smart, Elaine A. Moore, *Solid State Chemistry* (4th Edition), Taylor & Francis Group, Boca Raton, Florida, 2016, https://doi.org/10.1201/b12047.
10. Vázquez-Carson, S. F., Sun, Q., Dai, J., Mitra, D., & Zelevinsky, T. (2022). Direct laser cooling of calcium monohydride molecules. New Journal of Physics, 24(8), 083006.
11. El-Kork, N., AlMasri Alwan, A., Abu El Kher, N., Assaf, J., Ayari, T., Alhseinat, E., & Korek, M. (2023). Laser cooling with intermediate state of spin–orbit coupling of LuF molecule. Scientific Reports, 13(1), 7087.
12. de Jongh, T., Dash, G., Dixmerias, M., Salomon, C., & Yefsah, T. (2022). Simultaneous Sub-Doppler laser cooling of 6 Li and 7 Li isotopes. In APS Division of Atomic, Molecular and Optical Physics Meeting Abstracts (Vol. 2022, pp. S04-007).
13. Karl, R., Yin, Y., & Willitsch, S. (2024). Laser cooling of trapped ions in strongly inhomogeneous magnetic fields. Molecular Physics, 122(1-2), 2199099.
14. Vicente, R., Nogues, G., Niot, J. M., Wiertz, T., Contini, P., & Gardelein, A. (2020). Impacts of laser cooling for low earth orbit observation satellites: An analysis in terms of size, weight and power. Cryogenics, 105, 103000.
15. Tayfor, M. S. (2024). Physical properties of nano materials to act as nano capacitors using Schrodinger equation and treating electrons as strings. Journal of Energy Storage, 81, 110531.