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توسط

فاطمه شعبانی راد

ارائه شده به تحصیلات تکمیلی

به عنوان بخشی از فعالیتهای تحصیلی لازم جهت اخذ

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دکتر محمد مهدی گلشن (استاد راهنما)، استادیار بخش فیزیک

دکتر محمود براتی خواجوئی، دانشیار بخش فیزیک

دکتر عبدالناصرذاکری، استادیار بخش فیزیک

دکترحمید نادگران، استادیار بخش فیزیک

شهریور ۱۳۸۰

چکیـــــــده

تـوسط

فاطمه شعبـانی راد

در این رساله مبانی نظری پدیده سرمایش لیزری را ارائه می کنیم . برای این منظور بـه مطالعه بر همکنش میدان الکترو مغناطیسی (نور) و اتم ، در سه حوزه کلاسـیک ، نیمـه کوانتومی و کوانتومی ، می پردازیم . در ابتدا میدان و اتم هر دو بصورت کلاسیک در نظر گرفته می شود . سپس حالتی را در نظر می گیریم که میدان کلاسیک و اتم کوانتومی است و نهایتا حالتی را در نظر می گیریم که اتم و میدان هردوکرانتومی باشـــند . در دو مورد اخیر مدلی که برای اتمها در نظر گرفته شده است ، اتمهای دو تـرازه و سـه تـرازه خواهد بود .

در حالت اول با محاسبه نیروی وارد براتم نشان داده ایم که برهمکنش کلاســیک نـور و ماده تا حدی می تواند پدیده سرمایش را توجیه نماید . در این حــالت همچنیـن نشـان داده ایم که زمانی در حدود 10^{-4} ثانیه لازم اســت تـا ، در دمـای اتـاق ، انـرژی جنبشـی مجموعه ای از اتمهای سدیم (به عبارت دیگر ، دمای آن) بـه ۳۷ درصـد مقـدار اولیـه خود برسد . این محاسبات به اضافه دمای حدی (به عبارت دیگر کمترین دمایی که ، در حالت تعادل ، مجموعه به آن می رسد) را برای دو مورد نیمه کوانتومی و تمام کوانتومی نیز ارائه شده است . مقایسه بین نتایج دو مورد اخیر نشان میدهد که در این مدل دمای حدی یکسان بود ه و رفتار کوانتومی میدان الکترو مغناطیسی (نور) تـاثیر چندانـی در آن ندارد . مقایسه نتایج محاسبات نیمه کوانتومی و تمـام کوانتومـی بـا مـدل کلاسـیک فرآیند سرمایش لیزری ، همچنین نشان می دهد که در مدلهای کوانتومی نرخ سرمایش حدود صد مرتبه بزرگتر از مدل کلاسیک است .

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IN THE NAME OF GOD

THEORETICAL BASES FOR LASER COOLING

BY
FATEMEH SHAABANI RAD
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M. M. Golshan .... M. M. GOLSHAN, Ph. D.,ASSISTANT. PROF. OF PHYSICS (CHAIRMAN)
M. Barati-Khajooei .... M. BARATI, Ph. D., ASSOCIATE. PROF. OF PHYSICS
H. Nadgaran .... H. NADGARAN, Ph. D.,ASSISTANT. PROF. OF PHYSICS
A. Zakery .... A. N. ZAKERI, Ph. D.,ASSISTANT. PROF. OF PHYSICS

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ABSTRACT

THEORETICAL BASES FOR LASER COOLING

BY

FATEMEH SHAABANI RAD

In this thesis, the theoretical bases for laser cooling is presented. In so doing, we investigate the interaction between electromagnetic fields (light) and atoms in three regims of classical, semi-quantum mechanical and fully quantum mechanical physics. We begin our study by assuming that both the atoms and the field behave classically, so that classical electrodynamics applies. We then proceed to the cases where the atoms behave quantum mechanically, while the field is still classical. Finally, we advance the presentation to the cases where both entities behave quantum mechanically. In the quantum mechanical treatment (both semi and full) the atms are modled as having two and (or) three energy levels.

In the classical treatment, the force on a typical atom is calculated, showing that classical interaction of atoms and fields can cool the atomic system. In this case we also show that the kinetic energy (in other words, the temperature) of a collection of sodium atoms is reduced to %37 of its initial value (at room temperature), in a time of the order of 10^{-4} s. Furthermore, for the quantum mechanical cases we

have calculated the limiting (minimum) temperature for a collection of sodium atoms in thermal equilibrium. A comperison between the results of the last two cases shows that, within the approximations used in this work, the quantum behavior of the electromagnetic field (light) does not affect the limiting temperature.

Moreover, we show that the cooling rate obtained from the quantum mechanical models is about 10^2 times larger than its classical counterpart.

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CHAPTER 1

INTRODUCTION

The interaction of electromagnetic (EM) radiation (light) with atoms can be used to manipulate the dynamical behavior of atoms as well as to probe its structure. For example, in optical pumping, one can use the resonant exchange of angular momentum between atoms and polarized photons to orient the spins of the atoms and vice-versa [1]. Another use of such interactions is to decelerate atoms as well as to probe its structure [2]. This technique is known as ***laser cooling***, and relies on resonant exchange of linear momentum between photons and atoms to control the atomic external degrees of freedom and thus to reduce their kinetic energy [3]. In other words, laser cooling is the use of laser radiation to reduce the temperature of a collection of atoms.

Atoms cooled by laser cooling have been used in application to fields of Physics such as high-resolution spectroscopy [4-7], studies of collisions at low energies [8,9], study of condensed phases such as Coloumb crystals and Bose condensation [10], atomic clocks [11-13], surface physics [8] and collective quantum effects [14-17].

The possibility of changing the trajectory of atoms by resonant interaction with light was demonstrated as early as 1933 by Frisch [18], who reported the deflection of atomic beam, irradiated at right angle, by the resonant light from a discharge lamp. With the advancement of lasers, experimental aspects of optical cooling (as well as trapping) of ions and neutral atoms began to form the bases of many reports [19-21]. In this work we present a review of the theoretical foundations of " laser cooling".

The basic concept of "laser cooling ", simply stated, may be expressed as follows. When the moving atoms interact with the EM field of the laser, they gain energy (they become excited) and momentum. The excited atoms, in turn, spontaneously decay into lower states, thus loosing energy. Since spontaneous emission is random, on the average, atoms do not recoil because of this. If the laser beam is applied opposite to the atomic motion, the interaction causes the atoms to slow down (loosing kinetic energy) and thus the collection cools. Furthermore, because of the atomic motion, the resonance frequency, as seen by the atoms, is Doppler shifted, making the decelerating force velocity-dependent, similar to a first-order frictional force. In the literature, this phenomenon is referred to as "Doppler cooling ". The main aim of this work is to formulate the phenomenon of Doppler cooling in classical, semi-quantum and fully quantum-mechanical regimes of the interaction of EM fields and atoms [22].

Our work begins, in chapter two, with a review of the formulation of classical electrodynamics; Maxwell's equations and the Lorentz force. In this chapter we also present the Lagrangian and Hamiltonian formulations of the EM interaction. We further show that when a classical electric dipole is placed in an external electric wave, it experiences a decelerating force, giving rise to a lower temperature. In the same chapter we calculate the rate of energy loss and show that it would take about, 10^{-4}s to reduce the atomic (sodium) energy to %37 of its initial value.

In chapter three the semi-quantum formulation, in which the atoms are modeled as two-level entities, of the phenomenon of laser cooling is taken up. Within the electric dipole approximation and using the density matrix formulation, we show that the atom experiences a velocity-dependent decelerating force. The time interval, for which the energy is reduced to %37 of its initial value, is calculated to be of the order of 10^{-6}s. The results of this chapter show that the semi-quantum treatment (which is much closer to reality) gives rise to a cooling rate that is 100 times larger than the results of the classical treatment.

The full-quantum mechanical formulation of the laser cooling forms the subject of chapter four. In this chapter, after a brief account of the quantization of EM fields and time-dependent perturbation theory, we calculate the cross-section for spontaneous emission. From this cross-section we present the rate of energy loss and show that, within the same approximations, the cooling rate is identical to that of the semi-classical formulation.

Finally, in chapter five, some concluding remarks are made.

CHAPTER 2

THE INTERACTION BETWEEN ATOMS AND ELECTROMAGNETIC FIELDS IN THE CLASSICAL TREATMENT

The interaction of charged particles and the radiation field is most preciesly described by quantum electrodynamics, where both the particles and the field are quantized. Since the theory of quantum electrodynamics is based on the classical electrodynamics, a deeper insight into the former theory is gained from considerations of the latter. Therefore, this chapter is devoted to the interaction of nonrelativistic classical charged particles and classical Electromagnetic(EM) fields. Since both the classical and the quantum theories are based on ***Maxwell's equations and the Lorentz force***, a review of these equations is given. The classical dynamics of charged particles and EM fields is then developed, both in terms of a ***Lagrangian*** *and* a ***Hamiltonian***. Finally, the motion of an atom in an electromagnetic field is considered. Along these lines, we show that, under suitable conditions, the EM interaction decelerates the atoms which, in turn, reduces the temperature.

2.1 Maxwell's Equations and the Lorentz Force

The physical system to be considered here consists of a fixed number, N, of particles each having a mass m_α and a charge q_α $(\alpha = 1,2,...,N)$. The interaction of such a system with electromagnetic fields is governed by ***Maxwell's equations,*** which relate the time dependent electric and magnetic induction fields, $\vec{E}$ and $\vec{B}$, respectively, to the charge and current densities, ρ and $\vec{j}$, respectively. This equations are as follows (in Mks units) [23],

$$\nabla \cdot \vec{D} = \rho \tag{2.1.1}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{2.1.2}$$

$$\nabla \cdot \vec{B} = 0 \tag{2.1.3}$$

$$\nabla \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}, \tag{2.1.4}$$

with the ***constitutive relations***,

$$\vec{D} = \varepsilon_0 \vec{E} \tag{2.1.5}$$

and

$$\vec{B} = \mu_0 \vec{H}. \tag{2.1.6}$$

Here ε_0 and μ_0 are the free space ***permitivity*** and ***permeability***, respectively. In Eqs.(2.1.1)-(2.1.4), the fields are evaluated at spatial point $\vec{r}$ and time t. The first equation is ***Gauss's law***, the second one is ***Faraday's law***, the third one indicates the ***absence of magnetic monopoles***, and the last equation is the ***Ampere-Maxwell law***. If the position of the α th particle at a time t is denoted by $\vec{x}_\alpha$ (t), the charge and current densities in Eqs.(2.1.1) and (2.1.4) may be defined, respectively, as,

$$\rho(\vec{r},t) = \sum_{\alpha=1}^{N} q_\alpha \delta[\vec{r} - \vec{x}_\alpha(t)], \tag{2.1.7}$$

and

$$\vec{j}(\vec{r},t) = \sum_{\alpha=1}^{N} q_\alpha \dot{\vec{x}}_\alpha \ \delta[\vec{r} - \vec{x}_\alpha(t)], \tag{2.1.8}$$

where $\delta(\vec{x})$ is the Dirac delta function and $\dot{\vec{x}}_\alpha = d\vec{x}_\alpha / dt$ is the velocity of the αth particle. Maxwell's equations are consistent with charge conservation,

$$\nabla \cdot \vec{j}(\vec{r},t) + \frac{\partial}{\partial t}\rho(\vec{r},t) = 0, \tag{2.1.9}$$

which can be obtained by taking the divergence of Eq.(2.1.4) and using Eq.(2.1.1). The effect of the EM field on the charged particles is determined from the Lorentz force, which is experimentally determined to be [23],

$$m_\alpha \ddot{\vec{x}}_\alpha = q_\alpha[\vec{E}(\vec{x}_\alpha, t) + \dot{\vec{x}}_\alpha \times \vec{B}(\vec{x}_\alpha, t)]. \tag{2.1.10}$$

Maxwell's equations, Eq.(2.1.1)-(2.1.4), with Eq.(2.1.10) govern the dynamical behavior of the coupled system of the nonrelativistic charged particles and electromagnetic fields. Given a prescribed charge and current densities, one can solve these equations for the fields and vice-versa.

2.2 Vector and Scalar Potentials