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Investigation of Magneto-Optical Traps with Reduced Number of Laser Beams using a Monte Carlo Simulation

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1 Introduction

The deep understanding of light-matter interaction brought several scientific possibilities such as atom interferometry (1), accurate spectroscopic methods (2), and control of ultracold atoms. The Nobel Prize of Physics in 1997 was awarded jointly to Steven Chu (3), Claude Cohen-Tannoudji (4), and William D. Phillips (5) for developing methods to cool and trap atoms with laser light, also known as laser cooling (6). This achievement has enabled modern technologies, including accurate atomic clocks (7), qubits for quantum computing (8), and quantum sensors (9). Laser cooling also allowed the experimental confirmation of the degenerate quantum gas known as Bose-Einstein condensation (BEC), motivating the Nobel Prize of Physics in 2001 (10, 11).

The workhorse of laser cooling is the magneto-optical trap (MOT) (12), a technique to trap and cool a dilute atomic gas until temperatures in a range of μK. A standard

isto é correto mas não é preciso, se é que você me entende. eu prefiro algo do tipo three pairs of counterpropagating laser-beams mutually ortogonal to each other ou algo do tipo

MOT consists of six counter-propagating laser beams and a magnetic quadrupole field. Briefly, the atoms scatter photons from the laser light through atomic transitions, which causes a momentum exchange. The frequency of the scattering events is proportional to the natural linewidth[1] and affects several MOT properties such as atomic density, loading rate, and temperature. From a semiclassical perspective, the average momentum exchange yields a trapping and drag force on the atoms. MOTs using linewidths close to the photonic recoil[2], known as narrow-line magneto-optical traps (nMOTs)(13), can reach lower temperatures at the cost of trapping efficiency. esta frase parece meio perdida aqui

Recently, a two-species five-beam nMOT (14) employing gravity-assisted trapping was accomplished, bringing possibilities to elaborate MOTs with a reduced number of beams. However, the current quantitative theories for MOTs based upon the Doppler which quantities? cooling theory (15) give us a challenging task to predict some experimental quantities. The difficulty arises from the complex three-dimensional light in the presence of a magnetic complex three-dimensional light arrangement quadrupole field. Furthermore, the analysis of nMOTs is even more delicate since the typical semiclassical approach fails when one scattering event changes considerably the probability of the next one, which demands treating individual scatterings. A viable path is to simplify assumptions about the optical transitions and simulate the MOT dynamics (16).

We develop a Monte Carlo simulation to analyse the dynamics of atoms in nMOTs, aiming to predict experimental quantities of flexible beams configuration. Our model relies

flexible = flexivel, no sentido mecanico. fica melhor for alternative light geometries/arrangements/configurations.

[1] The natural linewidth Γ is the full width at half maximum (FWHM) of a Lorentzian spectral line broadening only by the time-energy uncertainty principle. The relation between Γ and the average lifetime τ of the excited state is given by $\tau = 1/(2\pi\Gamma)$.

[2] The photonic recoil ω_{recoil} is a frequency related to the energy shift ΔE caused by the absorption or emission of a single photon.

on sampling ensembles of random atomic trajectories as a discrete stochastic process, more precisely as a Markov chain. We also propose a trapping efficiency parameter to verify the feasibility of MOTs with a reduced number of beams. (I'll change this paragraph)

1.1 The Thesis

In the framework of this thesis, we perform a first study of light-matter interaction to understand MOTs and nMOTs from both a semiclassical perspective and a discrete momentum exchange through photons scattering. First of all, we investigate the basic concepts of absorption and emission of a light field considering the phenomenological Einstein rate equations. Afterwards, we perform a deep analysis solving the stationary solution of the optical Bloch equations. We also present some line broadening mechanisms. Lastly, we deduce the optical forces on the atoms using the previous stationary solution.

... I'm rewriting this part

2 Atom-light Interaction

In this chapter, we review several aspects of the interaction between an atom and light (17) to understand laser cooling properly. Firstly, we investigate the basic concepts of absorption and emission of light through *the phenomenological Einstein coefficients A and B*, which relies on the interaction between a two-level atom and a low-intensity light field. We shall analyze the case of high-intensity light characterizing an atom by a density matrix. Thus, we may solve *the optical Bloch equations* in a stationary condition considering both stimulated and spontaneous transitions. Lastly, we apply this solution to acquire an average force on the atoms called *optical force*.

2.1 Einstein's transition rates

A usual approach to introduce the essential aspects of atom-light interaction was proposed by Einstein in 1917. He defines phenomenological rate equations to describe the interaction between two-level atoms in a dilute atomic gas and low-intensity light[1] with spectral density energy $u(\omega)$. Einstein considers an atomic transition given by a two-level system whose energy difference between the upper and lower level is $\hbar\omega_0$, being $\hbar = h/(2\pi)$ the reduced Planck constant and ω_0 the resonant atomic frequency. Basically, there are three possible types of transition (I'll use a image here with the list bellow).

- **Stimulated absorption:** an atom in the lower level goes into the upper level induced by a light field with $u(\omega_0) > 0$;
- **Stimulated emission:** an atom in the upper level decays into the lower level in a presence of a light field with $u(\omega_0) > 0$, emitting a similar light field with the frequency ω_0;
- **Spontaneous emission:** an atom in upper level the lower level emits an isotropic light field with frequency ω_0 spontaneously, decaying into the ground state;

In all cases, the light field either loss or gain the energy $\hbar\omega_0$ due to energy conservation.

Let us consider a dilute atomic gas with number density $n_1(t)$ of atoms in the lower level and number density $n_2(t)$ of atoms in the upper level after a period of time t. The Einstein rate equations express the time evolution of n_1 and n_2 so that

$$\frac{dn_1}{dt} = -\frac{dn_2}{dt} = -B_{12}u(\omega_0)n_1 + B_{21}u(\omega_0)n_2 + An_2, \tag{2.1}$$

[1] The spectral distribution of the light flux is weak compared to the saturation intensity of the atomic transition, which will be introduced in section 2.2.

where $B_{12}u(\omega_0)$, $B_{21}u(\omega_0)$, and A are phenomenological rates associated with the stimulated absorption, stimulated emission and spontaneous emission respectively. The rates associated with stimulated processes are proportional to the spectral density energy and therefore theses processes only happen in the presence of a light field.

2.1.1 Relation between A and B

A dilute atomic gas at temperature T in thermal equilibrium establishes a steady state in which n_1 and n_2 are constants of time ($d_t n_1 = -d_t n_2 = 0$). Therefore, the spectral energy density given (2.1) is

$$u(\omega_0) = \frac{A}{(n_1/n_2)B_{12} - B_{21}}. \tag{2.2}$$

In the case of fixed number of atoms $n = n_1 + n_2$, we can analyze the atoms by the canonical ensemble, which associates the ratio n_1/n_2 with the Boltzmann distribution so that

$$\frac{n_1}{n_2} = \frac{g_1}{g_2} \exp\left\{-\frac{\hbar\omega_0}{k_B T}\right\}, \tag{2.3}$$

where g_1 and g_2 are the degeneracies of the lower and upper level, respectively, and k_B is the Boltzmann constant. Einstein evaluated atoms in a region of black body radiation, in which the spectral energy density of the light is consistent with the Planck distribution law given by

$$u(\omega_0) = \frac{\hbar\omega_0^3}{\pi^2 c^3} \frac{1}{e^{\hbar\omega_0/k_B T} - 1}. \tag{2.4}$$

Comparing (2.2), (2.3), and 2.4, we obtain

$$B \equiv B_{21} = \frac{g_1}{g_2} B_{12} \tag{2.5}$$

and

$$A = \frac{\hbar\omega_0^3}{\pi^2 c^3} B. \tag{2.6}$$

The Einstein coefficients are properties of the atom. Thereby the equations 2.6 and 2.5 are valid for any radiation, from narrow bandwidth radiation to broadband light. If we know one of the three rate coefficients, we can always determine the other two.

It is worthwhile to compare the spontaneous emission rate A to the stimulated emission rate $Bu(\omega_0)$ considering the equations (2.4) and (2.6) so that

$$\frac{A}{Bu(\omega_0)} = e^{\hbar\omega_0/k_B T} - 1. \tag{2.7}$$

The spontaneous emission dominates for high frequencies (visible, UV, X-ray), $\hbar\omega_0 \gg k_B T$, but the stimulated emission is more relevant for small frequencies (far IR, microwaves, radio waves).

2.1.2 Spontaneous and Stimulated Transitions on a Single Atom

Up to this point of the discussion or Previously or In the last section

Until the moment, we consider the effect of the Einstein equations an set of atoms. Now, we shall analyze the effect of those equations on a single atom. Let us consider the probability $P(t)$ of finding an atom in the upper level[2] after a period t given by

$$P(t) = \frac{n_2}{n_1 + n_2} = \frac{n_2(t)}{n}, \tag{2.8}$$

where $n = n_1 + n_2$ is the number of atoms in the sample. The probability distribution $\rho(t)$ of finding an atom in the upper level between the instants t and $t + dt$ is given by

$$\rho(t) = \frac{dP}{dt} = B_{12}u(\omega_0)(1 - P) - B_{21}u(\omega_0)P - AP = \tag{2.9}$$

$$= -\left[\left(1 + \frac{g_2}{g_1}\right) Bu(\omega_0) - A\right] P + \frac{g_2}{g_1} Bu(\omega_0), \tag{2.10}$$

where we use (2.1), (2.8), and $1 - P = n_1/n$.

The effect of the spontaneous emission can be shown considering an atom initially in the upper level ($P(0) = 1$) in the absence of light ($u(\omega) = 0$). In this case, given (2.10), we obtain

from Eq.

$$P(t) = e^{-At} \Rightarrow \rho(t) = Ae^{-At}. \tag{2.11}$$

remains

The average time τ ~~in~~ which an atom keeps in the upper level, also known as *lifetime*, is given by

$$\tau = \int_0^\infty t\rho(t)dt = \int_0^\infty Ate^{-At}dt = \frac{1}{A} \Rightarrow A = \frac{1}{\tau}. \tag{2.12}$$

In contrast, we can analyze the effect of stimulated processes considering the regime of low frequencies. Assuming $Bu(\omega_0) \gg A$, we obtain, given (2.10),

Assuming…. , from (2.10) we obtain

$$\frac{dP}{dt} + \left(1 + \frac{g_2}{g_1}\right) Bu(\omega_0)P - \frac{g_2}{g_1} Bu(\omega_0) = 0 \Rightarrow \tag{2.13}$$

$$P(t) = \left[P(0) - \frac{1}{2}\right] e^{-\alpha t} + \frac{1}{1 + g_1/g_2} \tag{2.14}$$

$$\text{and } \rho(t) = -\left(P(0) + \frac{1}{2}\right)\left(1 + \frac{g_2}{g_1}\right) Bu(\omega_0)e^{-\alpha t} \tag{2.15}$$

where $\alpha \equiv (1 + g_2/g_1)Bu(\omega_0)$. The equation (2.14) shows that the strong driving of a transition leads to its *saturation* ($P(t) \longrightarrow 1/(1 + g_1/g_2)$), in which medium becomes completely transparent.

the medium / the atomic ensemble

2.1.3 Absorption Cross-Section

In a more realistic situation, an atom can absorb non-resonant light due to line broadening mechanisms such as power broadening, Doppler effect, and collisions (section

[2] Analogously, we can define the probability of finding an atom in the lower level instead of the upper level.

2.2.2). The broadening effects can be taken into account through a normalized function $g_B(\omega)$ called line shape function, which defines the probability of absorbing a light field with a frequency between ω and $\omega + d\omega$. A common line-shape function in atomic spectroscopy is the Lorentzian

$$g_B(\omega) = \frac{\Gamma'}{2\pi} \frac{1}{(\omega - \omega_0)^2 + (\Gamma'/2)^2}, \tag{2.16}$$

where Γ' is full width at half maximum (FWHM) also known as spectral linewidth. Several broadening mechanisms results in a Lorentzian function, in which Γ' is expressed in different forms.

The power absorbed from a light field with spectral intensity distribution $I(\omega)$ by an atom is given by

$$\int_0^\infty \sigma(\omega) I(\omega) d\omega, \tag{2.17}$$

where $\sigma(\omega)$ is the *absorption cross-section*, a quantity that defines the fraction of absorbed light intensity. The stimulated absorption removes energy from the field, whereas the stimulated emission adds energy (amplification). Therefore, the equation 2.17 only contemplates the case of low-intensity light that leaves most of the atomic population in the lower level, causing a predominant effect of the stimulated absorption. For intense light fields and non-degenerate levels, the absorption cross section is $(1 - P)\sigma(\omega)$ and the emission cross section is $-P\sigma(\omega)$. Then, the total absorbed power is given by

$$\int_0^\infty (1 - 2P)\sigma(\omega) I(\omega) d\omega. \tag{2.18}$$

In thermal equilibrium, the absorption and emission reach a steady state, in which the difference between the stimulated absorption and stimulated emission equals the spontaneous emission. Therefore, the total absorbed power is related to the rate of energy loss by spontaneous emission as

$$PA \int_0^\infty \hbar\omega g_B(\omega) d\omega. \tag{2.19}$$

Equaling é muito esquisito.

Equaling the equations 2.18 and 2.19, we obtain

$$\sigma(\omega) = \frac{PA}{1 - 2P} \frac{\hbar\omega}{I(\omega)} g_B(\omega). \tag{2.20}$$

To obtain an complete expression for $\sigma(\omega)$ in terms of atomic and light properties, we need to calculate the probability P of finding an atom in the upper level and the line-broadening mechanism for g_B, which will be done in the section 2.2.

2.2 The Optical Bloch Equations

2.2.1 Stationary solution for two-level atoms

2.2.2 Line Broadening Mechanisms

2.3 Optical forces

3 Magneto-Optical Trap

3.1 Overview of Laser Cooling

3.2 Optical Molasses

3.3 Trapping effect

3.4 Narrow transitions

4 Simulation

5 Results

6 Conclusion

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