1 Introduction

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1.1 Motivation

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

singular

The workhorse of laser cooling is the magneto-optical trap (MOT) (11)~~s~~ a technique to trap and cool a dilute atomic gas until temperatures in a range of μK. A standard MOT consists of six orthogonal laser beams on a counter-propagating configuration and a magnetic quadrupole field whose origin matches the laser beams interception point. Briefly, the atoms scatter photons from the laser~~s~~ light through electronic transitions, which causes a momentum exchange. From a semiclassical perspective, the average momentum exchange yields a trapping and drag force on the atoms. The natural linewidth[1] is essential to define how often the momentum exchange will happen, affecting the minimum temperature. MOTs using linewidths close~~r~~ to the photonic recoil[2], known as narrow-line magneto-optical traps (nMOTs)(12), can reach lower temperatures at the cost of trapping efficiency. Furthermore, it is possible to produce spin-polarized atomic samples through nMOTs (13), which is desirable to avoid losses due to the dipolar relaxation (14).

confusing

no

atomic

but not only

too much

The current theories for the MOT based upon the Doppler 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 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 individuals scatterings. Therefore, there is a considerable interest in quantitative models capable of predicting MOT properties either to nMOTs or more complex systems like molecular MOTs (16). A viable path is to simplify assumptions

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[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 natural lifetime τ is related to Γ by the expression $\tau = 1/(2\pi\Gamma)$.

[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 with wave vector k ($\omega_{recoil} = \Delta E/\hbar = \hbar k^2/(2m)$).

what does it mean?

about the optical transitions and simulate the MOT dynamics (17), which allows the analysis of usual and unusual MOTs. Recently, a two-species five-beam nMOT (18) employing gravity-assisted trapping was accomplished. That brought possibilities to elaborate MOTs with a reduced number of beams. and ...

1.2 The Thesis

In the is thesis, we propose a Monte Carlo simulation to analyse the dynamics of atoms in nMOTs, aiming to predict experimental quantities. Our model assumes the scattering of photons as a stochastic process, specifically a Markov chain. Furthermore, we propose a trapping efficiency parameter to verify the feasibility of MOTs with a reduced number of beams. We obtain simulated data of six-beam nMOTs with dysprosium and strontium in agreement with experimental values. Moreover, we propose four and three-beam nMOTs, using simulated data and a semiclassical analysis to verify trapping efficiency and other properties like temperature and atomic cloud shape.

why?

In the framework of this thesis, we perform a first study of light-matter interaction to understand MOTs and nMOTs from a semiclassical and Quantum Optics perspective. First of all, we deduce the radiation pressure force through the stationary solution of the Optical Bloch Equations. After, we interpret this force as a process of absorption and spontaneous emission of photons. Then, we deduce a net force on the atoms in a low-speed regime, checking the limit for narrow transitions. only that?

The thesis is structured as follows. We initially introduce concepts of light-matter interaction in chapter 2. In particular, the interaction between a two-level atomic system and a classical electromagnetic field. Then, we present the MOT and nMOT theory in chapter 3, introducing a didactic unidimensional model and expending it to a three-dimensional configuration. Afterwards, we model the simulation as a Markov chain in chapter 4, showing an optimized implementation using parallel programming. In chapter 5, we check the simulation comparing simulated data with experimental values of nMOTs. We also present the analysis of nMOTs with four and three beams using a semiclassical picture and simulated results. ~~Furthermore~~, we summarize our findings and give an outlook to further possibilities in chapter 6.