Long Range Interactions With Laser Cooled Neutral Atoms

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Abstract. Multiple scattering of light in a trap of laser cooled neutral atoms leads to repulsion forces between the atoms. The corresponding interactions have long range behavior in $1/r^2$ and are thus similar to Coulomb interaction in an one component confined plasma. Consequences of these interactions will be described in this paper, including the limitation of the spatial density one can obtain in such systems and self-sustained oscillations of the cloud.

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INTRODUCTION

It is well known that radiation pressure can induce long range ($1/r^2$) repulsive interactions. This is for instance at the origin of one of the tails of comets and is also an important effect to explain the sizes of stars, where gravitational collapse is balanced by radiation pressure. Usually such effects are difficult to observe in laboratory experiments, as the radiation pressure forces (as well as gravitational forces) inside a system are small compared to external forces. Due to the strong resonances in atomic systems, laser cooled atoms however allow for radiation pressure forces to become observable and comparable to external confining forces. The presence of radiation pressure forces is at the origin of laser cooling and trapping proposed in 1975 [1], and first realized in 1987 [2]. The binary interaction due to multiple scattering has also been recognized early in the development of laser cooling [3]. However, as the consequence of this multiple scattering is a reduced spatial density of the atoms, this effect has been the main limitation for the realization of Bose-Einstein condensation with laser cooling techniques. And the first Bose-Einstein condensation of dilute atomic vapors has only been achieved with turning off the lasers and switching to evaporation in the final cooling stage [4]. This is probably the reason why multiple scattering of light by cold atoms has no longer been an important field of research. One exception to this is the quest for strong localization of light with cold atoms. Here interference effects of multiple scattering of light are important and the first observation of coherent backscattering of light by cold atoms has been realized in 1999 [5].

DENSITY LIMITATION IN MAGNETO-OPTICAL TRAPS

Laser cooling and trapping of atoms can conveniently be described at first by considering the dynamics of single atoms described by a damped harmonic oscillator:

$$\frac{d^2[\vec{r}]}{dt^2} = -\kappa r_1 - \gamma \vec{v} + \delta \vec{f}, \tag{1}$$

where κ is the spring constant of the so called magneto-optical trap (MOT), γ the friction coefficient and $\delta \vec{f}$ the fluctuating part of the forces, originating from the random scattering of photons by the atoms. All these coefficients depend on the laser parameters and we will restrict our discussion here to the simplest model (Doppler cooling with two level atoms) as proposed in [1]. It is also known that this is a very crude description of laser cooling and trapping, but to the extent that the qualitative features described in this paper can be described by this simple model we will neglect more subtle phenomena such as Sisyphus cooling and dark state cooling. In this regime, the size L of the atomic cloud is determined by the temperature and the spring constant. Increasing the number of atoms in the trap will then directly increase the spatial density of the atoms: $n = N/L^3$. The temperature of the cloud is also independent of the number of atoms. As one can reach temperatures of $T = 5\mu K$ with laser cooling and a size of $L = 200\mu m$ can be achieved, one could speculate that Bose-Einstein condensation could be reached for a critical atom number $N_{cr} = L^3 \zeta(3/2) \left[2\pi m k_B T / h^2\right]^{3/2} \approx 3\,10^{10}$.

However, as shown initially in [2], loading more atoms into the trap leads to an increased volume of the atomic cloud. Indeed, for a larger number of atoms in the trap, two additional effects have to be included in the estimation of the trap size. The first one leads to further compression of the cloud and is due to a shadow effect [6]. Atoms at one side of the cloud will be ‘screened’ by the rest of the cloud and not experience the same forces of all lasers beams. If this effect were to be(come) dominant in large atomic clouds, a runaway situation to ever larger atomic densities would be expected. This consideration however neglects the effects of the scattered photons. These photons are not only contributing to the attenuation of the incident laser beams, but they can also be reabsorbed by the other atoms of the cloud. This effect yields a repulsion force as photons scattered by an atom will tend to repel via radiation pressure nearby atoms. One can show that to leading order, both the repulsion force and the shadow effect have to be taken into account. The balance of theses two effects are very subtle and – unfortunately for Bose-Einstein condensation – the repulsion force dominate in all practical situations investigated up to now [2]. As the intensity of the light impeding at the second atom decreases as $1/r^2$, the corresponding radiation pressure yields a Coulomb type repulsion force with an effective charge of [7]

$$q_{eff} = \sqrt{\varepsilon_0 \frac{\hbar k \Gamma}{2} \frac{I_{inc}}{I_{sat}} \frac{\sigma_0}{\left(1+\frac{4\delta^2}{\Gamma^2}\right)^2}} \approx 10^{-4} . \qquad (2)$$

For simplicity let us then consider for now only the dominant effect, i.e. the binary repulsion between atoms due to multiple scattering. One can then show that the atomic density is given by:

$$n = \frac{\kappa}{G} , \qquad (3)$$

where G descries the above mentioned repulsion forces. Many efforts have been deployed to circumvent this limitation, the best known being the so-called dark SPOT technique, which makes use of the internal hyperfine structure of the atoms [8]. One mayor limitation to such schemes is that pumping atoms into another hyperfine level also reduces the spring constant of the trap.

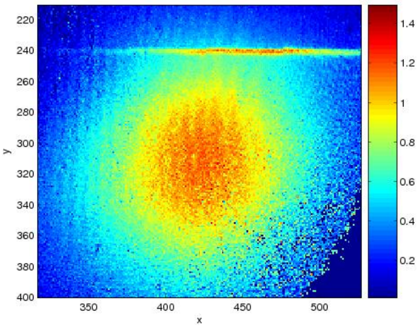

FIGURE 1. Absorption image of atoms released from a dark dipole trap. The parameters of the dipole laser are: beam waist = 350µm, power = 0.25W, detuning = 20GHZ. After loading 10^{10} atoms into a large MOT for 5seconds, 2 10^8 atoms are loaded for 50ms into the dark dipole trap, leading a density of $n \approx 10^{12}$ atoms/cc. The dipole trap has an axial frequency estimated to 0.2Hz, a radial frequency of 400Hz and a depth of 2mK.

We have therefore combined the dark SPOT technique with a quasi-resonant dipole trap and thus increased the spatial density by a factor 20 compared to a standard MOT. In Figure 1 we show an absorption image of the atomic cloud 50ms after switching off the MOT [9]. One can clearly see the atoms in free fall released from the MOT and the atoms hold in the dipole trap (narrow line). This technique needs further investigations to study the ultimate limit of atom number and density in such a dark dipole trap.

COLLECTIVE EXCITATIONS IN MAGNETO-OPTICAL TRAPS

Once the static effects of multiple light scattering understood, one can now turn to dynamic studies of collective effects with cold atoms. We have identified one spectacular manifestation of such phenomena: a self-sustained oscillation of the size of the atomic cloud [7]. This oscillation is reminiscent of heartbeat oscillations which occur in many non linear oscillators. A one dimensional numerical simulation of our system confirmed a simple one-zone model for the threshold of this instability: when the Zeeman shift at the edge of the cloud equals the laser-atom detuning, active motion is induced in the outer parts of the MOT in contrast to the damped motion in inner layers of the MOT. As shown in Figure 2 more complex spatio-temporal structures are predicted. This opens the way for fascinating future studies of long range interactions with cold atoms, including recent prediction of Tonks-Dattner resonances.

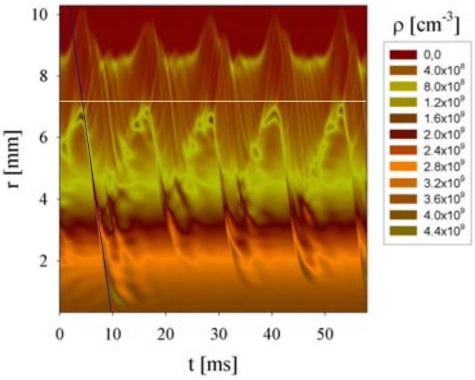

FIGURE 2. Numerical prediction of radial density distribution of the atomic cloud.

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