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Self-sustained oscillations in a Large Magneto-Optical Trap

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We have observed self-sustained radial oscillations in a large magneto-optical trap (MOT), containing up to $10^{10}$ $^{85}$Rb atoms. This instability is due to the competition between the confining force of the MOT and the repulsive interaction associated with multiple scattering of light inside the cold atomic cloud. A simple analytical model allows us to formulate a criterion for the instability threshold, in fair agreement with our observations. This criterion shows that large numbers of trapped atoms $N > 10^9$ are required to observe this unstable behavior.

A large fraction of the stars in the upper Hertzsprung-Russell diagram present pulsations based on an interplay between modulated radiation pressure effects, which tends to increase the size of the star, and a collapse based on gravitational forces [1]. Instabilities also occur in other similar systems such as confined plasmas where a long range Coulomb interaction has to be countered by a confining force to avoid an explosion of the plasma [2]. These systems are of fundamental importance for astrophysics and for controlled fusion and have thus been extensively studied in the past. However it is either impossible (in the case of stars) or extremely difficult (in the case of confined plasmas) to perform experiments to study the full dynamics of such systems where collective effects play a dominant role. On the other side, allowing for adequate rescaling, alternative systems can present similar dynamics. A variety of interesting collective effects have thus been identified in charged colloidal systems [3]. Recently ultra-cold plasmas created by ionizing a cloud of laser cooled atoms became subject to increased attention [4]. Beyond the possibility of studying analogous effects as in astro- and plasma physics, systems with long range interactions are known to lead to non-extensive behavior and appropriate scaling laws are needed to predict macroscopic properties. Here we show that a large cloud of laser cooled atoms is an adequate system to study such collective effects. The radiation pressure of the multiply scattered photons in such clouds can indeed be related to a long range Coulomb type interaction [5]. We thus suggest an analogy between the dynamics of a large cloud of cold atoms, astrophysical systems and plasma physics.

The effect of multiple scattering on the dynamics of the atoms is well known in the community of laser cooling of atoms, as multiple scattering has been a major limitation to obtain large phase space densities in cold atomic traps. Bose-Einstein condensation (BEC) in dilute atomic vapors has only been achieved after switching off all laser fields and using evaporation techniques [6]. More recently, multiple scattering of light in cold atoms has been used to study coherent light transport in random media [7]. This has led to an investigation of yet unexplored regimes, namely the limit of very large number of cold atoms in the presence of quasi-resonant light. Here we do not focus on the properties of the scattered light but on the mechanical effects of this light on the atoms. We have observed collective instabilities triggered by the repulsive interatomic force arising from multiple scattering, and identified a supercritical Hopf bifurcation separating the standard stable MOT operation from a yet undescribed unstable regime.

In order to estimate the relevance of plasma physics considerations to study multiple scattering of light by cold atoms it is worth deriving the equivalent of several plasma parameters for our system. The analogy with an $1/r^2$ repulsive Coulomb-type force [5] is obtained from evaluating the power scattered by one atom ($P_{\text{scatt}}$) and deriving the intensity incident $I_2$ on a second atom via $I_2 \propto P_{\text{scatt}}/(4\pi r^2)$. The resulting radiation pressure force scales as $1/r^2$ and one can thus define an effective charge $\tilde{q}$ which depends on the absorption cross sections and laser intensity and is typically $\tilde{q} \approx 10^{-4} e$ [8]. A total interaction energy $\tilde{q}V = \frac{N\tilde{q}^2}{4\pi a R}$ larger than the kinetic energy $k_BT$ of the particles leads to an increased diameter $L = 2R$ of the magneto-optical trap when the number $N$ of atoms exceeds $10^{10}$. Alternatively the Debye length $\lambda_D = \sqrt{e\tilde{q}k_BT/4\pi n\tilde{q}^2}$ above which collective effects become important is of the order of 100$\mu\text{m}$, well below the typical size of a large MOT (several mm). Also, in our experiments the corresponding plasma frequency $\omega_D = \sqrt{n\tilde{q}^2/m_0}$ is slightly larger ($\approx 200\text{Hz}$) than relaxation rate of the atomic positions ($\approx 50\text{Hz}$). We thus expect our cloud to behave as a weakly damped plasma. Another interesting quantity is the ratio between the nearest neighbor Coulomb interaction and the kinetic energy $\Gamma_{\text{Cb}} = \frac{\tilde{q}^2}{\sqrt{4\pi n\tilde{q}^2}/k_BT}$ with $a \approx n^{-1/3}$ [9]. We estimate this quantity to be smaller than unity in our system, excluding thus any crystallization. An important aspect of these light induced collective interactions is that the effective charge $\tilde{q}$ depends on experimental control parameters, allowing for a engineering of the ef-
the trap. A repumping laser on the dependent Zeeman shift yielding the restoring force of \( \nabla d \) (\( \delta \) line by \( D )

We thus obtain a MOT with up to a dilute vapor using six large independent beams. Below a critical number of atoms \( N_{th} \), the size of the atom cloud increases without specific dynamical behavior. Above the threshold \( N_{th} \) the cloud switches to an unstable mode characterized by periodic oscillations in the partial fluorescence signal. Inserts: Fourier transform of signal, with (a) a flat noise in the stable regime and (b) distinct oscillations in the unstable regime.

Our cloud of cold atoms is confined in a MOT using laser-induced forces [13]. We collect \( \text{Rb}^{85} \) atoms from a dilute vapor using six large independent laser beams (beam waist \( 4 \, \text{cm} \), power per beam \( P = 30 \, \text{mW} \)) thus avoiding the intensity imbalance and feedback mechanism responsible for the instability of ref [12]. Under standard operating conditions, the trapping lasers are detuned from the \( F = 3 \rightarrow F' = 4 \) transition of the \( D2 \) line by \( \delta = -3 \Gamma \) (\( \Gamma/2\pi = 6 \, \text{MHz} \)). A magnetic field gradient (\( \nabla B \approx 10 \, \text{G/cm} \)) is applied to generate a spatially dependent Zeeman shift yielding the restoring force of the trap. A repumping laser on the \( F = 2 \rightarrow F' = 3 \) of the \( D2 \) line is used to control the total number of atoms. We thus obtain a MOT with up to \( N = 10^{10} \) atoms (diameter \( L = 5 \, \text{mm} \), \( T = 80 \mu \text{K} \))[13]. The size and shape of the cloud is monitored by imaging the MOTs fluorescence on a cooled CCD. The optical thickness \( b \) of the cloud at the trapping laser frequency is measured by a photodiode. To obtain a time-resolved information on the local density of the MOT, we also image a portion of the cloud on another photodiode.

Fig. 1 illustrates the onset of spontaneous self-sustained oscillation for a sufficiently large number of atoms. We switched on the MOT at \( t = 0 \) and monitored the time evolution of the fluorescence from a portion of the MOT.

This partial fluorescence signal is roughly describing the number of atoms in the observed region. Starting from \( N = 0 \) at \( t = 0 \), the trap fills with a time constant \( \tau = 1.45 \, \text{s} \) determined by the ambient Rb pressure. Below a critical number of atoms \( N_{th} \), the size of the atom cloud increases with number of trapped atoms [13] but no specific dynamical behavior is observed. Above the threshold \( N_{th} \) the cloud switches to an unstable behavior characterized by periodic oscillations in the partial fluorescence signal. These radial oscillations of the cloud are self-sustained in the sense that no external modulation of any control parameter is present.

In the inserts of Fig. 1 are shown Fourier transforms of the partial fluorescence. Below the instability threshold (insert a) a flat noise background is obtained. In contrast, in an unstable MOT, obtained for a larger number of atoms, distinct oscillation frequencies (insert b) appear, with higher harmonic components indicating the non-harmonic oscillation of the signal.

Indeed, the dynamics in the unstable regime can be more complex than a harmonic oscillation, as further illustrated in Fig. 2 where we detect the fluorescence from the center of the MOT. A high contrast modulation of the center fluorescence is observed in this experiment. We can speculate that to the fast phase of decrease of the signal corresponds a MOT expansion (decreased density at the center), whereas we associate the increasing part of the fluorescence to a slower compression phase. We observed that the precise shape of this oscillation depends on the laser beam alignment and on the monitored region of the MOT. However, the threshold separating the stable from the unstable regime was found to be very robust with respect to trap parameters.

Investigating the MOT at the instability threshold by

**FIG. 1:** Fluorescence of part of the MOT during a loading sequence. Below a critical number of atoms \( N_{th} \), the size of the atom cloud increases without specific dynamical behavior. Above the threshold \( N_{th} \) the cloud switches to an unstable mode characterized by periodic oscillations in the partial fluorescence signal. Inserts: Fourier transform of signal, with (a) a flat noise in the stable regime and (b) distinct oscillations in the unstable regime.

**FIG. 2:** Fluorescence of the MOT center. In the unstable regime, periodic oscillations appear in the absence of external modulations.
Already in the stable regime, we observed some clear indications that strongly increasing the number of trapped atoms affects the way the MOT operates. As it is well-known, the MOT inflates when atoms are added as a consequence of multiple scattering of light. In addition to the standard $L \propto N^{1/3}$ law, we found for large number of atoms $N > 10^9$ a different scaling $L \propto N^{1/2}$, which manifests as oscillations of the center-of-mass which drives the behavior of our large MOT.

To explain the apparition of this new instability, we developed a simple model where the screened compression force of the MOT is competing against the repulsive interaction due to multiple scattering of light inside the cloud. We stress that this instability is thus qualitatively different from that studied in ref.[4], where the use of retro-reflected beams introduces the feedback necessary for the instability. The instability process of ref.[12], which manifests as oscillations of the center-of-mass of the MOT, does not involve the long-range interatomic interactions which drives the behavior of our large MOT.

We propose in the following a very simple 1-zone model which exhibits an instability threshold. This model amounts to an extremely simplified mean field theory, based however on microscopic expressions for the light forces acting on the atoms. A more refined approach, beyond the scope of this paper, could e.g. involve hydrodynamical approximations.

We assume an homogeneous density and the size of the cloud $L$ is related to the density $n$ via the total number of atoms $N$: $n = N/L^3$. The dynamics along one symmetry axis ($Ox$) of a probe particle located outside of the cloud (at position $x > R$ from the trap center, with a velocity $v$) is then governed by the force:

$$F(x, v) = \frac{\hbar k \Gamma}{2} s_{\text{inc}} \frac{e^{-b}}{1 + \left|\frac{\delta - \mu x - kv}{1 + \Gamma}\right|^2}$$

$$= \frac{\hbar k \Gamma}{2} s_{\text{inc}} \frac{1}{1 + \left|\frac{\delta + \mu x + kv}{1 + \Gamma}\right|^2}$$

$$+ \eta \frac{\hbar k \Gamma}{2} s_{\text{inc}} \frac{1}{1 + \frac{\Gamma^2}{1 + \eta^2} (1 - e^{-b})(\frac{R}{x})^2}$$

This expression relies on the low intensity Doppler model for the magneto-optical force (incident on-resonance saturation parameter $s_{\text{inc}}$). The first term in
dynamics near threshold are confirmed by recent results from a more involved model [17], which includes the inhomogeneous density distribution inside the cloud (N-zone model).

We have described in this paper the observation of self-sustained oscillation in a large cloud of laser cooled atoms, arising from the competition between the MOT’s confining force and the long range multiple scattering repulsive interaction. This new instability process affects the behavior of large MOTs containing more than $10^9$ atoms, a regime increasingly found e.g. in experimental setups producing BECs. This observation shows that large clouds of cold atoms still present a rich dynamics with a variety of yet unexplored regimes. A simple 1-zone model has been presented which allows to predict the instability threshold and to understand the underlying physical mechanism. Future possible investigations include the forced oscillation regime, the spectroscopy of excitation modes in this system, gas-liquid-crystal phase transitions in the degenerate regime and feedback mechanisms allowing for stabilization of a large cloud of interacting particles. Progress on the theoretical aspects of the systems described in this paper include exploiting mean field theory and molecular dynamic simulations. This should allow for a better understanding of the bifurcation observed in our experiment and lead to study statistical (thermodynamic) properties across the threshold. If the degenerate regime could be reached (or inducing similar interactions in a Bose Einstein Condensate) a mean field theory based on binary collisions as in usual Gross Pitaevskii equation will not be valid due to the long range interaction, connecting this system to strongly correlated quantum systems.

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