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From superradiant Rayleigh scattering to Bragg scattering

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Abstract. We present the results of an experiment on light scattering from an elongated Bose-Einstein condensate interacting with far off resonant laser light. Due to superradiant Rayleigh scattering a coherent superposition of two atomic wavepackets with different momenta forms in the presence of a single laser beam. Varying the intensity of a weak counterpropagating laser beam we observe the transition from the pure superradiant regime to the Bragg scattering regime, where Rabi oscillations in a two-level system are observed. The process is limited by the decoherence between the two atomic wavepackets.

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1 Introduction

Bose-Einstein condensates (BECs) of dilute atomic samples have proven to be important tools for the investigation of fundamental aspects of quantum mechanics in macroscopic systems [1]. In particular, the long range coherence and the extremely small momentum spread of a BEC allow a detailed study of the effects of collective atomic recoil in the interaction with far off resonant light. The spontaneous formation of a regular density grating in a BEC was first observed in superradiant Rayleigh scattering experiments [2], and then used as the gain process in the amplification of matter waves [3]. This effect is the same as the one observed in collective atomic recoil lasing (CARL) [4]. The matter wave grating is the result of the coherent superposition of different atomic momentum states, similar to the one produced in Bragg scattering experiments in which matter is diffracted by a standing wave of light [5]. In all these experiments the coherence in the atomic superposition plays a crucial role. Effects, such as spontaneous emission, inhomogeneous broadening and collisions in the atomic sample, may destroy the coherence in the matter wave field and seriously inhibit the superradiant process [6]. In this paper we show the transition from superradiance to Bragg scattering in the presence of a weak optical grating.

The experiment is performed with an elongated ^{87}Rb BEC exposed to an off-resonant laser pulse (*pump beam*) directed along the condensate symmetry axis (see Fig. 1). The laser is far detuned from any atomic resonance, so that resonant absorption is suppressed and the only scattering mechanism present is Rayleigh scattering [2]. In an elongated condensate a preferential direction for the scattered photons emerges, causing superradiant Rayleigh scattering. In this regime the atoms, initially scattered randomly, interfere with the atoms in the original momentum state creating a matter-wave grating with the right periodicity to further scatter the laser photons in the same mode. Both the matter-wave grating and the scattered light are then coherently amplified. This process is more efficient along the direction where the condensate is

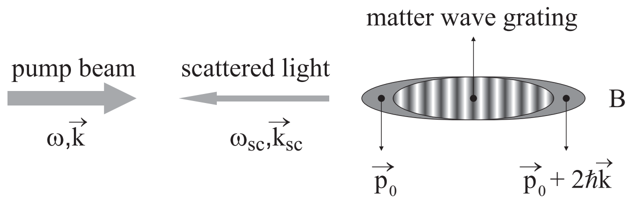

Fig. 1. Schematics of superradiant light scattering from a Bose-Einstein condensate. An elongated BEC is illuminated by a far off-resonant laser beam (pump beam) with frequency ω and wavevector $\mathbf{k}$ directed along its axial direction. After backscattering of photons with $\mathbf{k}_{sc} \simeq -\mathbf{k}$ and the subsequent recoil of atoms, a matter wave grating forms, due to the quantum interference between the two momentum components of the wavefunction of the condensate. The effect of this grating is to further scatter the incident light in a self-amplifying process.

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elongated, therefore, in our geometry, photons are backscattered with $\mathbf{k}_{sc} \approx -\mathbf{k}$, where $\mathbf{k}$ is the wave-vector of the laser photon, and the atoms gain a recoil momentum $2\hbar\mathbf{k}$. The efficiency of the process, arising from the self-bunching of the matter-wave field, is limited by the decoherence between the original and the recoiled atomic wavepackets, causing damping of the matter-wave grating. In a recent paper [7] we presented preliminary results on the influence of the external atomic motion on decoherence in superradiant Rayleigh scattering. In the experiment described in this paper we stimulate the superradiant amplification with a counterpropagating laser field (*seed beam*) at the right frequency to induce stimulated Bragg transitions between the two momentum states involved in the superradiant process. When the Rabi frequency of the stimulated process is larger than the superradiant gain, the dynamics of the system is completely dominated by Rabi oscillations. In this paper we present experimental results on the transition from the superradiant regime to the Bragg scattering regime, in full agreement with the theoretical model introduced in [8].

The paper is organized as follows. In Section 2 we present the experimental set-up while in Section 3 we discuss the experimental results in the frame of the CARL theory.

2 Experimental set-up

We produce a cigar-shaped BEC of ^{87}Rb in a Ioffe-Pritchard magnetic trap by means of RF-induced evaporative cooling. The axial and radial frequencies of the trap are $\omega_z/2\pi = 8.70(7)$ Hz and $\omega_r/2\pi = 90.1(4)$ Hz respectively, with the z-axis oriented horizontally. After the end of the evaporation the trap is suddenly switched off and the cloud expands and falls down under the effect of gravity (see Fig. 2). After 2 ms of free expansion, when the magnetic trap field is completely switched off and the atomic cloud still has an elongated shape (at this time the radial and axial sizes of the condensate are typically 10 and 70 μm, respectively), a square pulse of light is applied along the z-axis.

The condensate is illuminated by a pump laser with frequency ω and intensity I and, in some experiments, by a counterpropagating seed beam with frequency ω_s and intensity $I_s = \eta I$. The duration of the two laser pulses is controlled by two independent acousto-optic modulators, driven by two different phase-locked radiofrequencies in order to provide a stable frequency difference $\delta = \omega - \omega_s$. We set the frequency difference between the two beams $\omega - \omega_s = 4\omega_R$ to be resonant with the Bragg transition for the condensate with initial momentum $p_0 = 0$, with $\omega_R = \hbar k^2/2m \simeq 2\pi$ 3.77 kHz the recoil frequency of a rubidium atom. The two beams are derived from the same Ti:Sapphire laser which is red-detuned $\Delta_0 = 15$ GHz away from the rubidium D2 line at $\lambda = 780$ nm. The pump beam typically has an intensity $I \simeq 0.9$ W/cm^2. The seed beam, when present, has a much weaker intensity, from 10^{-5} to 10^{-3} of the pump beam intensity. The linearly polarized laser beams are collimated and aligned along the z-axis of the condensate. The size of the laser beams is larger than 0.5 mm, far larger than the distance covered by the condensate during the interaction with light. In this geometry the superradiant process causes the pump light to be backscattered and the self-amplified matter-wave propagates in the same direction as the incident light. In presence of seeding we expect the backscattered light to have the same frequency $\omega_{sc} = \omega_s$ of the seed beam. Setting up the experiment we carefully avoided unwanted reflections of the pump beam in the same direction of the seed beam. To this aim the laser beams have been aligned at a nonzero angle with respect to the normal to the vacuum cell windows where the BEC is produced. After an expansion of 28 ms, when the two momentum components are spatially separated, we take an absorption image of the cloud along the horizontal radial direction. In Figure 2C we show a typical absorption image in which the left peak is the condensate in its original momentum state p_0 and the right peak is formed by atoms recoiling after the superradiant scattering at $p_0 + 2\hbar k$. The spherical halo centered between the two density peaks is due to non-enhanced spontaneous processes, i.e. random isotropic emission following the absorption of one laser photon [2]. From a 2D-fit of the pictures, assuming a double Thomas-Fermi density distribution, we extract the number of atoms in both the original and the recoiled peaks. We study the population in the two momentum states as a function of the duration of the laser pulse for various experimental conditions.

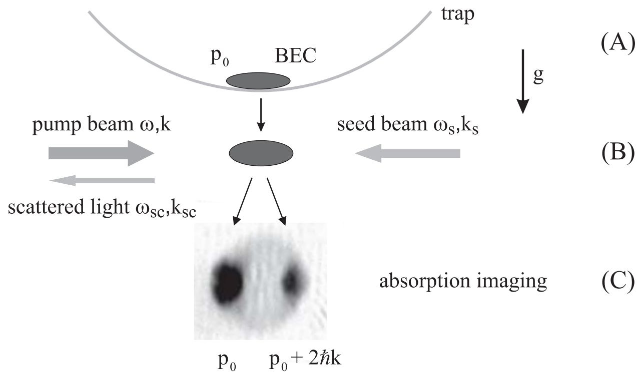

Fig. 2. Sketch of the experimental procedure. The condensate is released from the magnetic trap with initial momentum $p_0 = 0$ and falls down under the effect of gravity (A). We flash the atoms with far off resonance laser light (pump and seed beams) directed along the condensate symmetry axis (B). After an expansion time allowing a complete separation of the momentum components p_0 and $p_0 + 2\hbar k$ (28 ms) we take an absorption image of the atoms (C).

3 Experimental results

We observe the transition from the Bragg scattering regime to the superradiant regime by varying the intensity ratio $\eta = I_s/I$ of the seed beam to the pump beam.

In Figure 3 we show the evolution of the population in the original momentum state $p_0 = 0$ as a function of

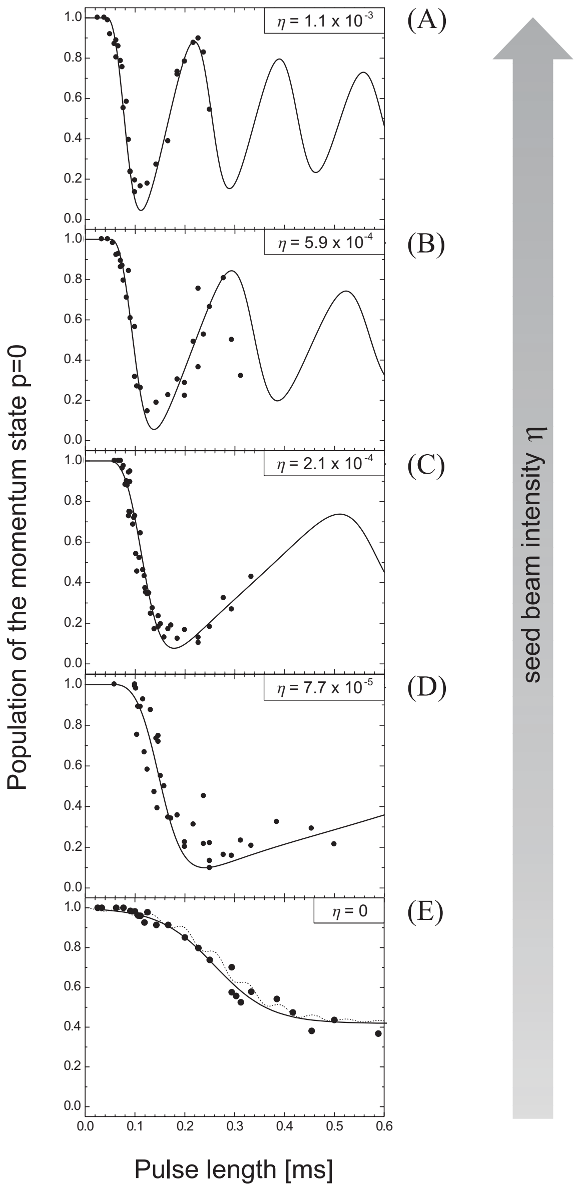

Fig. 3. Time evolution of the population in the original momentum state $p_0 = 0$ for a BEC interacting with an off-resonant pump beam and a counterpropagating weak seed beam (resonant with the Bragg transition $\omega - \omega_s = 4\omega_R$) for different seed beam intensities $I_s = \eta I$. The laser detuning and intensity are 15 GHz and 0.9 W/cm^2 respectively. As the seed intensity decreases (from top to bottom) the response of the system goes from the Bragg scattering regime to the pure superradiant regime. The solid lines in figures A, B, C, D are obtained from the numerical integration of equations (1–3). In figure E the solid line is a fit to the data using equation (4).

the pulse length for several values of the seeding parameter η from 0 to 1.1×10^{-3}. With our experimental parameters we observe only two momentum components in the expanded cloud, so that we can use the two-level approximation as in [8]. The data in Figure 3A correspond to $\eta = 1.1 \times 10^{-3}$. In this case the population performs a weakly damped Rabi oscillation caused by Bragg transitions between the two momentum states $p_0 = 0$ and $p = 2\hbar k$. Reducing the seed beam intensity, this oscillation becomes strongly damped and starts to show an asymmetric shape (Figs. 3B, 3C and 3D). Eventually, when the seed beam is absent (Fig. 3E), the population in the original momentum state slowly decays to a stationary value.

This observed dynamics is well accounted for by a theoretical model based on the CARL-BEC equations [7]:

$$\frac{dS}{dt} = gAW - \gamma S \tag{1}$$

$$\frac{dW}{dt} = -2g(AS^* + h.c.) \tag{2}$$

$$\frac{dA}{dt} = gNS + i\Delta A - \kappa(A - A_{in}), \tag{3}$$

where g is an effective coupling coefficient, $\kappa \approx c/2L$ (L is the condensate length) is the field loss coefficient, S represents half of the amplitude of the matter wave grating, W is the population fraction difference between the two atomic states, A and A_{in} are the slowly varying amplitudes of the scattered and seeding fields respectively, $\Delta = \omega - \omega_s - 4\omega_R$ is the detuning from the Bragg resonance with the scattered field and γ is the decoherence rate.

In absence of the seed beam the model gives an analytical solution in the form of a hyperbolic tangent describing the depletion in the original momentum state due to the superradiant scattering

$$P = 1 - \frac{1}{2}\left(1 - \frac{2\gamma}{G}\right)\left\{1 + \tanh\left[(G - 2\gamma)\frac{(t - t_0)}{2}\right]\right\}. \tag{4}$$

The continuous line in Figure 3E is the fit of this function to the experimental data, giving the values $G = 30.8(3.5)$ ms^{-1} for the superradiant gain, $\gamma = 6.4(9)$ ms^{-1} for the decoherence rate of the atomic superposition and $t_0 = 0.26(1)$ ms for a phenomenological delay time as best parameters. The dotted line is instead the result of the full numerical integration of equations (1–3). In this case we have introduced for A_{in} a noise field with frequency $\omega_s = \omega$ to trigger the onset of the superradiant amplification [8–10]. We have chosen the amplitude of this injected field to be $I_N = 70$ μW/cm^2, corresponding to $\eta_N = 7.8 \times 10^{-5}$, in such a way to obtain the best agreement with the experimental data. We define this value of the intensity as the "equivalent input noise" for this experimental set-up.

In the presence of the seed beam the system may undergo stimulated Bragg transitions between the two momentum states $p = 0$ and $p = 2\hbar k$. When the intensity of the seed beam is much larger than the peak of the superradiant intensity, this effect is dominant and the population oscillates at the Rabi frequency of the two-photon transition. In the intermediate regime, when the intensities of the two beams are very unbalanced ($\eta \approx 10^{-4}$), the dynamics of the system is driven by the interplay between the two processes, resulting in asymmetric oscillations in which the depletion of the original momentum state is faster than its repopulation. The continuous lines in Figures 3A, 3B, 3C and 3D are the results of the numerical integration of equations (1–3) using the parameters G, γ obtained in absence of seeding. The comparison between the curves and the experimental points confirm the validity of the theoretical model in describing this intermediate regime.

We would like to discuss the role played by the presence of some backscattered light in our set-up. In an experimental apparatus it is very difficult to avoid the presence of light backreflected by the vacuum cell windows. In particular, considering the 1D geometry of our experiment, if some counterpropagating light exists, this could cause off–resonant stimulated Bragg scattering of atoms in the same direction and with the same transfer of momentum $2\hbar k$ as the superradiant process but with a frequency of the backscattered light $\omega_s = \omega$. This mechanism would actually mask the effect of a pure superradiant scattering. Indeed, in our experimental set-up we detected the back-diffusion of a small amount of light, caused by the poor quality of the cell windows. We estimated the magnitude of this light by directly measuring with a power-meter the intensity backscattered collinearly to the pump light. This intensity is 7×10^{-6} W/cm^2, corresponding to $\simeq 8 \times 10^{-6}$ of the pump intensity. This observation confirms that, in all the experiments described above, we should take into account the presence of some counterpropagating light at the same frequency ω of the pump and a relative intensity of $\simeq 10^{-5}$.

4 Conclusions

In conclusion, we have experimentally studied superradiant light scattering from an elongated Bose-Einstein condensate. In the experiment, performed adding a counterpropagating beam, we have explored the transition from the pure superradiant regime to the Rabi oscillations regime induced by stimulated Bragg scattering. We give an analytical expression for the limiting case of pure superradiance. In the intermediate regime we have resorted to a numerical integration of the full system of equations.

The fully quantized version of the CARL-BEC model offers the possibility of investigating the realisation of macroscopic atom-atom or atom-photon entanglement [11,12]. The results obtained in this work represent a step in this direction.

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