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## Diffraction of a Released Bose-Einstein Condensate by a Pulsed Standing Light Wave

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We study the diffraction of a released sodium Bose-Einstein condensate by a pulsed standing light wave. The width of the momentum distribution of the diffracted atoms exhibits strong oscillations as a function of the pulse duration, corresponding to periodic focusing and collimation of the condensate inside the standing light wave. Applications of this thick grating regime of diffraction to atom interferometry are discussed.

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Coherent atom optics is a new and rapidly developing area of atom physics. We have used a standing wave optical potential to create a diffraction grating with which we have studied the normal incidence temporal diffraction of an adiabatically cooled Bose-Einstein condensate (BEC). The use of an atomic BEC as an atom optical source has clear advantages over a thermal source: (1) The BEC source is several orders of magnitude brighter because of very high phase space density. (2) The rms atomic momentum is much less than the recoil momentum of a single photon, so diffraction orders are well separated. (3) Atoms are spatially well localized compared to the Gaussian envelope of the laser beam forming the standing wave, so the illumination is uniform, with a step-like temporal envelope. This is in contrast to atomic beam experiments, where there is a longitudinal momentum spread of the atomic beam, and atoms experience the full variation of the spatial envelope of the light over different times.

The normal incidence diffraction of atoms by light [1–4] was experimentally studied more than ten years ago with atomic beams interacting with continuous standing waves [5]. All of these experiments were performed in the thin grating limit [4], in which the interaction time,  $\tau$ , of the atoms with the light is so short that their displacement along the standing wave can be neglected. With a BEC atomic source, we have extended this experimental range to implement a thick grating limit of diffraction, when  $\tau$  is comparable to or longer than the vibrational period of the atoms in the standing light wave. Under these conditions, oscillations in the symmetric redistribution of the momentum and the spatial distribution of diffracted atoms have been predicted theoretically [4,6]. Here, we observe such periodic collapses of the momentum splitting of the BEC, which have not been seen before. In related atom lithography experiments, the interaction time of atoms with the standing wave is fixed to focus them inside the standing light wave and to deposit them on a solid substrate [7] (these experiments use only the first most sharp focus). Furthermore, chromatic aberrations and surface diffusion of deposited atoms [8] makes comparison of these experimental results with theory rather inaccurate. Earlier experiments which also observed such

channeling of atoms [9] were dominated by dissipation due to spontaneous emission and did not resolve individual diffracted momentum peaks.

We consider the diffraction of atoms by a plane standing light wave pulse with a field amplitude  $E(z, t) = 2E_0 f(t) \cos(kz) \sin(\omega t)$ , where the function  $f(t)$  describes the unit square pulse of duration  $\tau$ , and  $k = 2\pi/\lambda$  is the wave number. We assume the magnitude of the detuning,  $|\Delta| = |\omega - \omega_0| \gg \Omega_0, \Gamma$ . Here  $\omega$  is the light frequency,  $\omega_0$  is the frequency of the resonant atomic transition,  $\Omega_0 = \mu E_0/\hbar$  is the traveling wave Rabi frequency,  $\mu$  is the dipole matrix element, and  $\Gamma$  is the natural width of the transition. During the pulse, atoms in the ground state experience the potential

$$U(z) = U_0 \cos^2(kz), \quad (1)$$

where  $U_0 = \hbar\Omega_0^2/\Delta$ . The minimum classical oscillation period is  $t_v = \pi\sqrt{|\Delta|/\Omega_0^2\omega_r}$ , where  $\omega_r = \hbar k^2/2M$  is the recoil frequency, and  $M$  is the mass of the atom.

For  $\tau \ll t_v$  the standing wave can be treated as a thin phase grating that modifies the atomic de Broglie wave with a phase modulation given by  $\phi(z) = U(z)\tau/\hbar = \phi_0 \cos^2(kz)$ , where  $\phi_0 = \Omega_0^2\tau/\Delta$  is the peak amplitude of the phase modulation. An atom with zero momentum is therefore split by the standing wave into multiple components with momenta

$$p_n = n2\hbar k, \quad (n = 0, \pm 1, \pm 2, \dots), \quad (2)$$

with populations  $P_n = J_n^2(\phi_0/2)$ , where  $J_n(z)$  are Bessel functions of the first kind [3].

For  $\tau \gtrsim t_v$  the diffraction of atoms is fundamentally different. Modification of the de Broglie wave can no longer be described by a phase modulation and thin grating theory no longer applies. Instead, atoms oscillate in the wells of the standing wave potential, periodically focusing and defocusing. We observe this periodicity in momentum space as an oscillation of the populations in the different momentum components. Classically, the anharmonicity of potential (1) tends to destroy this periodicity. In our strongly quantal experiment, however, the potential is so shallow that only two vibrational quantum states are highly occupied. So, in our case, the periodicity hardly deteriorates, and strong collapses in momentum

width are observed. The maximum momentum gain during each period of oscillation is  $p_{\max} \approx \sqrt{2|U_0|M}$ , which provides a good estimate for the maximum significantly populated diffraction order [4]  $n_{\max} = \sqrt{|U_0|/(4\hbar\omega_r)}$ .

The experiment was organized as follows. With a combination of laser and evaporative cooling we produced in about 30 s a BEC consisting of about  $10^6$  sodium atoms in the  $3S_{1/2}(F=1, m_F=-1)$  state in a time-averaged orbiting potential (TOP) magnetic trap. Subsequently, the spring constant of the trap was adiabatically decreased by a factor of 100 in 0.5 s in order to decrease the momentum spread of condensate. The final diameter of the adiabatically expanded BEC was about  $60 \mu\text{m}$  and the principal oscillation frequencies of the trap were  $\omega_x \approx 16 \text{ Hz}$ ,  $\omega_y \approx 23 \text{ Hz}$ , and  $\omega_z \approx 32 \text{ Hz}$ , where  $x$  is vertical.

The standing light wave used for diffracting the BEC was produced by a dye laser, locked to the  $3S_{1/2}(F=1) \rightarrow 3P_{3/2}(F'=2)$  transition of sodium for which  $\Gamma/2\pi = 10 \text{ MHz}$ . The frequency was shifted  $\Delta/2\pi = -420 \text{ MHz}$  to the red side of this transition by an acousto-optical modulator (AOM). This AOM was also used for rapidly switching on and off the standing wave in less than 30 ns. After passing through the AOM, the beam was sent through a single mode fiber to provide a clean  $\text{TEM}_{00}$  spatial mode. Then, the beam was expanded to a  $1/e^2$  diameter of 2.8 mm, sent through a linear polarizer, passed through the vacuum chamber containing the BEC, and retroreflected. The intensity maximum of the transverse profile of the standing wave was made coincident with the location of the BEC. The total power in the laser beam was about 1 mW, corresponding to a peak Rabi frequency  $\Omega_0/2\pi \approx 16 \text{ MHz}$ . Because of possible misalignment between the true intensity center of the beam and the location of the BEC, the Rabi frequency could be up to 20% less than the calculated maximum value.

In all experiments the BEC was suddenly released from the magnetic trap and allowed to expand for 2 ms. It would be more correct to call the released BEC a cold coherent atomic wave packet expanding in free space, but in accordance with existing terminology we also call it a BEC. To produce diffraction, a short pulse of horizontal standing wave light was then applied. After an additional time of flight of 10 ms, the horizontal spatial distribution of the diffracted atoms was detected using a standard absorption imaging method [10] with a vertical probe beam.

In Fig. 1 we present several images of the horizontal spatial distributions of the diffracted BEC atoms after interacting with standing wave pulses of different durations. These data were taken at 1:1 magnification with an 8-bit CCD camera having a spatial resolution along the direction of the standing wave of  $17 \mu\text{m}$ . From these images one can see how the population of higher order momentum states first grows, then saturates, and finally (for  $\tau = 3 \mu\text{s}$ ) converges down to a nearly pure undiffracted distribution. We have also observed similar oscillations for larger durations of the standing wave pulse up to  $12 \mu\text{s}$  (see Fig. 3

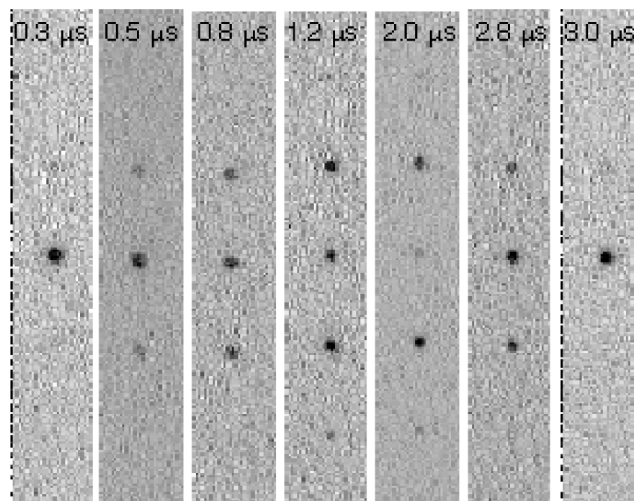


FIG. 1. Spatial distribution of the optical depth of the BEC diffracted by a standing wave pulse of various durations. The corresponding duration of the pulse is shown above each individual distribution.

below). The maximum number of observed diffraction orders (five peaks) is in agreement with the calculated value of  $n_{\max} = 2$ , for our parameters.

In Fig. 2 we show the distribution of diffracted atoms along the  $z$  axis for  $\tau = 1.2 \mu\text{s}$ . This figure is the result of selecting a narrow strip of pixels along the diffraction direction within the data and integrating the content of the pixels along the perpendicular rows. The inset shows the  $n = -1$  diffraction peak. The size of the inset is  $400 \mu\text{m}$ . By using the Thomas-Fermi model [11] of the expansion of the BEC we calculated the rms momentum width of the atomic ensemble at the moment of application of the light standing wave to be about  $p_{\text{rms}}^{(i)} = (0.02 \pm 0.002)\hbar k$ .

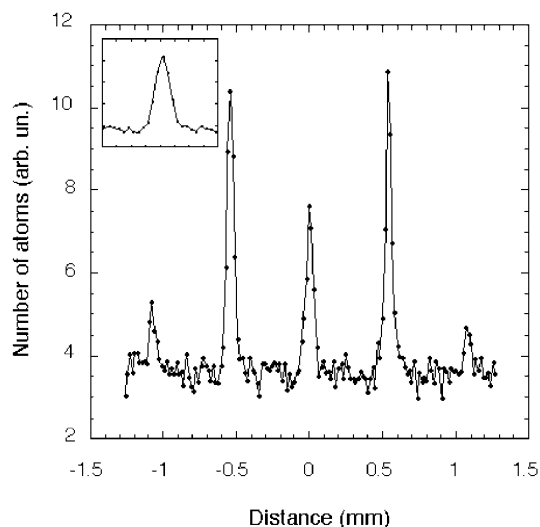


FIG. 2. Spatial profile of the integrated number of atoms of the split BEC along the  $z$  axis of the standing light wave. The duration of the standing wave pulse was  $\tau = 1.2 \mu\text{s}$ . The inset is an enlargement of the  $n = -1$  diffraction peak.

We integrate the area under each of the peaks in the images to extract the relative number of atoms in each diffraction order. Shown in Fig. 3(a) is the dependence of the number of atoms in the  $n = 0$  and in each of the  $n = \pm 1$  diffraction peaks [Fig. 3(b)] as a function of the duration of the standing wave pulse. We found that for short pulse duration,  $\tau \leq 1 \mu\text{s}$ , the splitting is well described by thin grating theory. In Fig. 3, one can see three collapses of the BEC motion, manifested as an absence of splitting of the BEC at  $\tau = 3.2, 6.5,$  and  $10 \mu\text{s}$ . The maximum number of atoms in the  $n = \pm 1$  peaks [Fig. 3(b)] was observed between these times. This behavior can be explained as an alternating sequence of squeezing of the whole atomic distribution in coordinate (focusing) and momentum (collimation) space in a standing wave potential with period  $t_c \approx 3.2 \mu\text{s}$ . The  $\sim 10\%$  fluctuation of the amplitudes of the diffracted peaks was a result of the corresponding fluctuation of the number of atoms in the BEC from shot to shot.

The decrease in the total number of atoms in the diffraction peaks in Fig. 3 for  $\tau \sim 10 \mu\text{s}$  is explained by the continuous excitation of a small population of atoms to the upper electronic state with subsequent fast emission of spontaneous photons, giving atoms a recoil momentum  $\hbar k$  in a random direction.

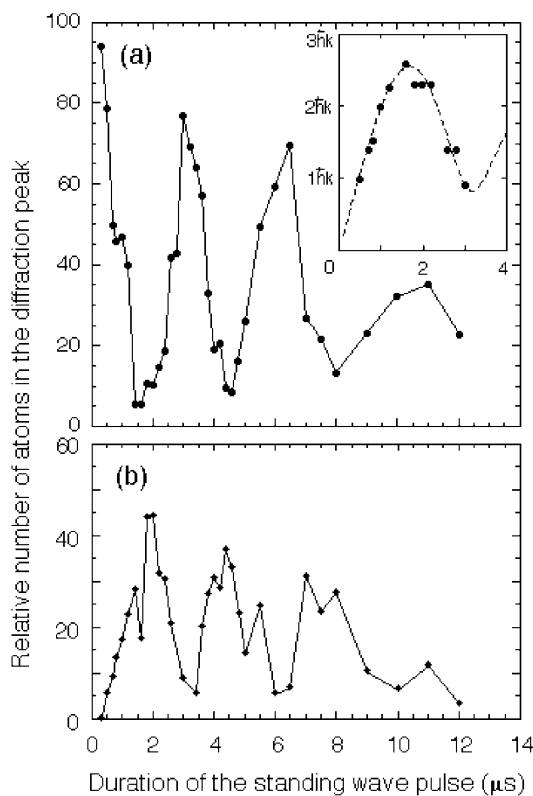


FIG. 3. Dependence of the relative number of atoms in  $n = 0$  (a) and  $n = 1$  (b) diffraction orders as a function of standing wave pulse duration  $\tau$ . The inset shows the dependence of the rms momentum width  $p_{\text{rms}}$  of the diffracted atoms on  $\tau$ .

In Fig. 4(a) we present a calculation of the dependence of the intensities of the main diffracted peaks on the duration of the standing wave pulse, obtained by the numerical solution of the linear Schrödinger equation for a two-level atom. The two-level model is a good approximation because the detuning of the standing wave is much larger than the hyperfine splitting of the upper atomic state. A traveling wave Rabi frequency  $\Omega_0/2\pi = 14 \text{ MHz}$ , detuning  $\Delta/2\pi = -420 \text{ MHz}$ , and a Gaussian initial momentum distribution with  $p_{\text{rms}}^{(i)} = 0.005\hbar k$  were used [12]. These calculations agree very well with the experimentally obtained curves of Fig. 3, both yielding  $t_c = 3.2 \mu\text{s}$ . (This time is about 23% larger than  $t_v/2 \approx 2.6 \mu\text{s}$ , which can be explained by the anharmonicity of the sinusoidal potential.) The calculated minimum rms spatial width of the focused atomic ensemble in a single well of the optical potential is  $z_{\text{rms}} \approx 20 \text{ nm}$  at  $\tau = 1.54 \mu\text{s}$  [see Fig. 4(b)]. Furthermore, the calculated phase space density of these atoms satisfies  $z_{\text{rms}} p_{\text{rms}} \approx \hbar/2$ , near values of  $\tau$  for which atoms are maximally focused. Here  $p_{\text{rms}}$  refers to the rms momentum width of the entire ensemble. Based on the measured relative amplitudes of the individual  $n = 0, \pm 1, \pm 2$  diffraction peaks, we have calculated  $p_{\text{rms}}$  of the diffracted atoms for

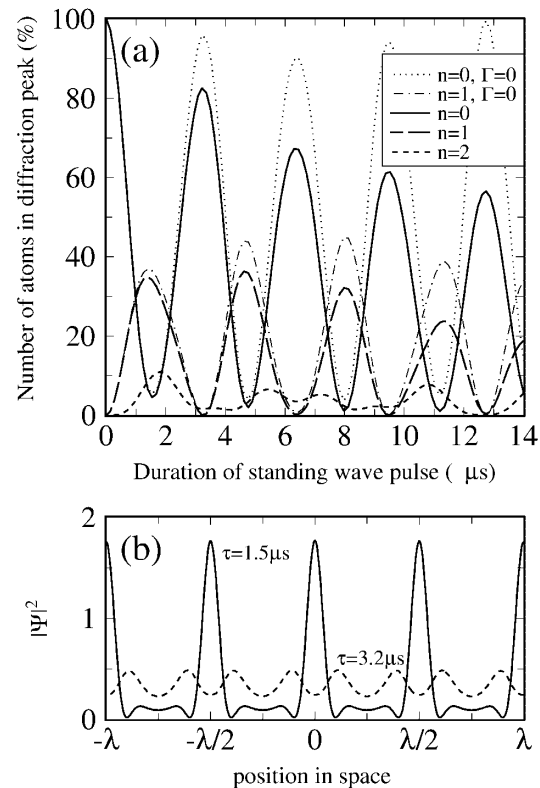


FIG. 4. (a) Calculated population in  $n = 0$  (solid curve),  $n = 1$  (dashed curve), and  $n = 2$  (dotted curve) diffraction peaks as a function of standing wave pulse duration  $\tau$  (see text for definition of dotted-dashed line); (b) calculated atomic spatial distribution at  $\tau = 1.5$  and  $3.2 \mu\text{s}$ .

$\tau$  varying from 0 to 4  $\mu\text{s}$ . This is indicated in the inset of Fig. 3(a) by the dots, which are in good agreement with the dashed theory curve.

We have also calculated the energies of the eigenstates and their populations for the atoms in the standing wave potential with a total depth  $U_0 = -19.26\hbar\omega_r$ . There are only three bands (labeled  $\nu = 0, 1, 2$ ) of allowed states below the potential barrier [6]. Therefore the interaction of atoms with the standing wave has a completely quantum character. At all times after the light is suddenly turned on, the atoms are distributed over states near the center of the Brillouin zone of only the three, lowest-energy, even bands; the spatially symmetric initial wave function has zero projection on the antisymmetric states in odd bands. The energies and occupations of these states are  $E_0 = -15.14\hbar\omega_r$ ,  $W_0 = 59.1\%$ ;  $E_2 = -2.28\hbar\omega_r$ ,  $W_2 = 38.2\%$ ;  $E_4 = 7.37\hbar\omega_r$ ,  $W_4 = 2.7\%$ . Therefore, we have a strongly nonclassical system consisting mainly of two populated vibrational states, with a beat period of  $2\pi\hbar/(E_0 - E_2) = 3.1 \mu\text{s}$  between them, which is in very good agreement with the experimentally observed period of atomic motion  $t_c$ . The longer beat period observable in Fig. 4(a),  $2\pi\hbar/(E_0 + E_4 - 2E_2) = 12.5 \mu\text{s}$ , is due to the small population of the third vibrational level  $E_4$ .

We have found that, in the thick grating limit and for the small amplitude of the standing wave potential ( $n_{\text{max}} \approx 2$ ), it is possible to split atoms into just two diffraction components,  $n = \pm 1$ , separated in momentum space by  $4\hbar k$ . We observed such a splitting experimentally for  $\tau = 2$  and  $4.5 \mu\text{s}$ . The calculation shows that, in the absence of spontaneous emission, the total number of atoms in the  $n = \pm 1$  diffraction peaks for  $\tau = 8 \mu\text{s}$  can be as large as 90% [dotted-dashed curve in Fig. 4(a)]. Such a laser “biprism” for atoms might be very useful for atom interferometers.

In conclusion, we have observed diffraction of a coherent atomic sample by a pulsed standing light wave. Periodic collapses of the momentum splitting of the diffracted atoms were observed. The general technique of temporal atom optics of supercold BEC atoms used in our experiment is very promising for further studies of other phenomena, such as atomic beam splitters [13] and temporal atom interferometers [14]. This method permits investigation of the limiting resolution of atom lithography in the absence of chromatic aberrations and surface diffusion of deposited atoms [8].

We recently learned that similar oscillations of the momentum distribution of diffracted atoms were observed for a thermal beam of metastable argon atoms [15].

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