Coherent Splitting of Bose-Einstein Condensed Atoms with Optically Induced Bragg Diffraction

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We have observed Bragg diffraction of a Bose-Einstein condensate of sodium atoms by a moving, periodic, optical potential. The coherent process of Bragg diffraction produced a splitting of the condensate with unidirectional momentum transfer. Using the momentum selectivity of the Bragg process, we separated a condensate component with a momentum width narrower than that of the original condensate. By repeatedly pulsing the optical potential while the atoms were trapped, we observed the trajectory of the split atomic wave packets in the confining magnetic potential. [S0031-9007(98)08316-1]

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Atom optics, the manipulation of atoms in analogy to the control of light with optical elements, has seen rapid advances in recent years. Of particular interest are applications that rely on the de Broglie wave nature of atoms, such as diffraction and interferometry [1]. One such technique is Bragg diffraction by an optical standing wave [2–4], which provides coherent splitting of matter waves with unidirectional momentum transfer. With the advent of Bose-Einstein condensation of dilute atomic gases [5–8], a coherent source of matter waves analogous to an optical laser is now available. Bragg diffraction preserves the condensate's coherence properties while providing efficient, selectable momentum transfer. In this Letter, we report Bragg diffraction of a Bose-Einstein condensate (BEC) of sodium atoms by a moving, periodic optical potential.

Bragg diffraction will be a versatile technique for manipulating Bose-Einstein condensates. It will be useful as an output coupler for an atom laser [9] because the large momentum transfer produces a directed output beam and the process is coherent [10]. Bragg diffraction can manipulate a condensate in a trap, creating multiple, coherent components whose interaction and interference can be studied. The Bragg process is also sensitive to the initial momentum of an atomic wave packet, allowing one to impart a well defined momentum to the condensate while having a negligible effect on the uncondensed fraction. This may allow studies of the interactions between the condensed and noncondensed portions of the gas, such as damping, or atom-atom scattering stimulated by bosonic enhancement.

When an atomic beam passes through a periodic optical potential formed by a standing light wave and interacts with it for a sufficiently long time, it can Bragg diffract, analogous to the Bragg diffraction of x rays from a thick crystal. In each case the incident beam must satisfy a condition on the angle of incidence. Our Bragg diffraction is instead performed on a stationary BEC. In contrast to the diffraction of an atomic beam, the interaction time is determined not by the passage of the atoms through a standing wave, but by the duration of a laser pulse. The condition on the angle of incidence becomes a condition on the frequency difference between the two beams comprising the standing wave, or equivalently, the velocity of the moving standing wave. Bragg diffraction under these conditions can also be thought of as stimulated optical Compton scattering [11], a recoil-induced resonance [12,13], or as a stimulated Raman transition between two momentum states [14–16].

nth order Bragg diffraction by a moving, optical standing wave can be viewed as a $2n$-photon stimulated Raman process in which photons are absorbed from one beam and stimulated to emit into the other [Fig. 1(a)]. The initial and final momentum states form an effective two-level system coupled by the multiphoton Raman process. Conservation of energy and momentum require

$$\frac{(nP_{\text{recoil}})^2}{2M} = n\hbar\delta_n,\tag{1}$$

where $P_{\text{recoil}} = 2\hbar k \sin(\theta/2)$ is the recoil momentum from a two-photon Raman process, $k = 2\pi/\lambda$; λ is the wavelength of the light, M is the atomic mass, and δ_n is the frequency difference between the two lasers. For our conditions first-order Bragg diffraction is resonant at $\delta_1/2\pi = 98$ kHz and higher orders at $\delta_n = n\delta_1$.

In our experiment, we produce a BEC as described in detail elsewhere [17]. Briefly, about 10^{10} Na atoms are optically cooled and trapped in a dark magneto-optical trap [18]. They are transferred into a magnetic quadrupole field where atoms in the $3S_{1/2}$ $F = 1, m_F = -1$ state are trapped, compressed, and then cooled by rf-induced evaporation. Before the atoms are lost in the zero field region in the center of the trap, a time-averaged orbiting potential (TOP) [19] trap is created by suddenly turning on a rotating bias field. The bias field rotates in the x-z plane, where x is the quadrupole axis and z is vertical along the direction of gravity. Our TOP trap differs from the design of [19] in that our bias field rotates in a plane that includes the quadrupole symmetry
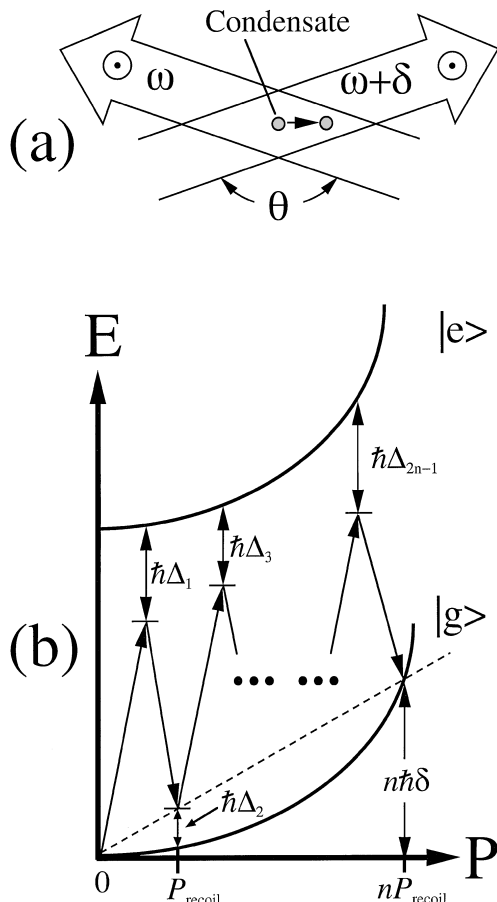
axis. The ratio between spring constants along the x, y, and z directions is $K_x{:}K_y{:}K_z = 4{:}2{:}1$. The atoms are compressed in the TOP trap and cooled by evaporation to form a BEC. We obtain a condensate with about 10^6 sodium atoms having no discernible uncondensed fraction in a trap with harmonic frequencies of $\omega_x/2\pi = 360$ Hz, $\omega_y/2\pi = 250$ Hz, $\omega_z/2\pi = 180$ Hz.

Our first experiments were performed on Bose-condensed atoms released suddenly from the TOP trap. The trap is turned off in 50 μs and the BEC undergoes expansion driven by the mean-field repulsion between the atoms. After a few characteristic times $\tau = (\omega_x\omega_y\omega_z)^{-1/3}$, the mean field is negligible and the cloud expands ballistically [20]. During this ballistic expansion the condensate is exposed to a moving, periodic optical potential generated by two nearly counterpropagating ($\theta = 166°$) laser beams with parallel linear polarizations but slightly different frequencies [Fig. 1(a)]. These (phase coherent) laser beams are derived from a single laser ($\lambda = 589$ nm) using acousto-optic modulators. The intensity of each beam is 23 mW/cm^2, and the common detuning with respect to the $3S_{1/2}$, $F = 1 \rightarrow 3P_{3/2}$, $F' = 2$ transition is $\Delta/2\pi = -1.85$ GHz. To transfer all the atoms to the desired momentum state, we empirically choose laser intensities and pulse durations to give a π pulse for the effective two-level system. We use two pulses with frequencies ω and $\omega + \delta$ that overlap for 55 μs [21]. The probability of spontaneous emission is less than 0.05.

Figure 2(a) is an image taken just before the Bragg pulse is applied. The atoms are first optically pumped into the $3S_{1/2}$ $F = 2$ ground state. They are then absorption imaged [5] with probe light on the $F = 2 \rightarrow F' = 3$

FIG. 1. Experimental arrangement of the laser beams (a) and partial transition diagram (b) for nth order Bragg diffraction. The parabolas correspond to the $P^2/2M$ kinetic energy.
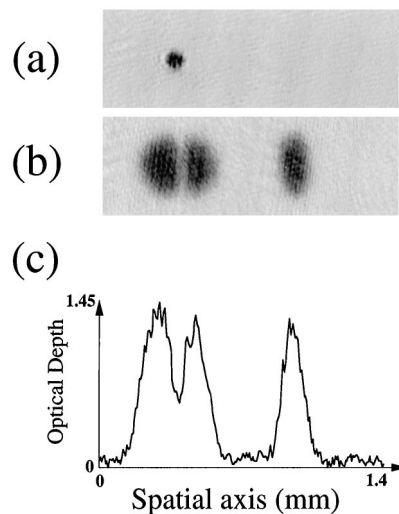

FIG. 2. Optical absorption image of a Bragg diffracted condensate. (a) An image taken just before the moving standing wave pulse is applied. (b) is taken after a time of flight of 10 ms. (c) is a line profile taken through the center of the expanding clouds.

transition. The probe propagates opposite to gravity and is orthogonal to the plane that contains the Bragg beams. From different time-of-flight images taken after the mean field becomes negligible, we determine the rms momentum width of the released BEC. Along the direction of momentum transfer we measure $\Delta P_{rms} = 0.30(4)\hbar k$ (all uncertainties in this paper represent one standard deviation combined statistical and systematic uncertainties). Figure 2(b) is an image taken 10 ms after the Bragg pulse (which occurs 2 ms after the BEC is released). A slice is removed from the center of the atomic momentum distribution and is displaced by $P_{recoil} \sim 2\hbar k$. The slice appears because the resonant width of the Raman transition in momentum space is narrower than ΔP_{rms} of the released condensate. From these images, we have determined the rms momentum width of diffracted atoms along the direction of the momentum transfer to be $0.16(1)\hbar k$. The resonant width of the Bragg diffraction can be calculated from an integration of the optical Bloch equations for a two-level system with a time dependent two-photon Rabi frequency. In our case, the calculated peak two-photon Rabi frequency is $\Omega_2/2\pi = 30$ kHz, and the predicted width is $0.08\hbar k$, a factor of 2 less than measured. We do not have an explanation for this difference, although it may be due in part to residual mean-field effects [22].

This analysis implies that we can Bragg diffract the entire cloud of atoms if the pulse duration τ is short enough such that $\tau^{-1} \gg 2k\Delta P_{rms}/M$, and the intensity is sufficient for a π pulse. To achieve this we reduce the rms momentum width of the BEC by adiabatically expanding the trap. The axial gradient of the quadrupole field is linearly ramped down from 9.2 to 0.71 T/m in 2 s while the bias field is increased from 1.0 to 1.2 mT. This reduces the frequencies ω_i of the TOP trap by a factor of 14. Even for this weak trap, the size of the condensate is determined by the mean-field interaction. In this Thomas-Fermi limit, the asymptotic momentum spread of the released BEC decreases as $\omega^{3/5}$ [23]. The rms momentum width of the released condensate after adiabatic cooling should be $\frac{1}{5}$ of the width of a condensate released from the tight trap. This is in qualitative agreement with the observed expansion in time-of-flight images. (The adiabatically expanded condensate is so cold that it undergoes little expansion during the time of flight, so its momentum spread cannot be accurately measured.)

After adiabatic expansion, the BEC is released from the TOP trap and expands for 2 ms. The Bragg pulse is applied and the atoms are imaged 5.6 ms later. When the difference δ between the two laser frequencies is zero, Eq. (1) is not satisfied and diffraction does not occur [Fig. 3(a)] because the Fourier transform width of the 55 μs pulse is small compared to 98 kHz. When $\delta/2\pi = 98$ kHz, first-order Bragg diffraction [Fig. 3(b)], with up to 100% efficiency, is observed. In Fig. 3(b) we chose the diffraction efficiency to be less than 100% so that the original position of the BEC was visible.
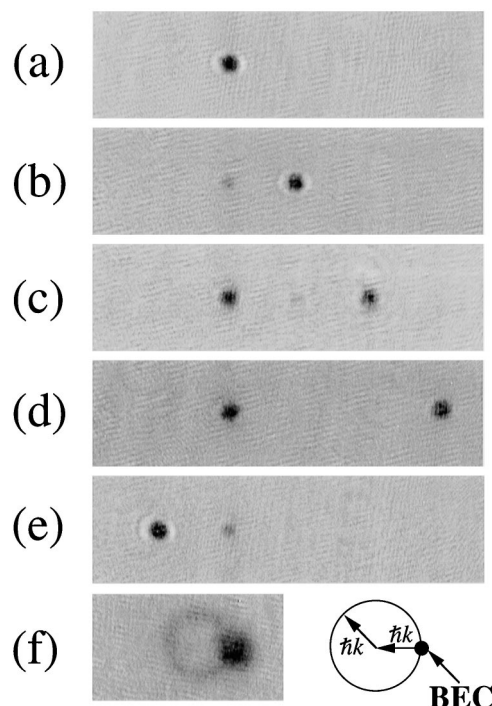

FIG. 3. Optical depth images of condensates which were first adiabatically expanded and then Bragg diffracted. (a), (b), (c), (d), and (e) are images taken 5.6 ms after Bragg pulses with frequency differences of $\delta/2\pi = 0$, 98, 200, 300, and -98 kHz, respectively. (f) is an image where spontaneous emission occurred using a single laser beam. The width of the field of view is 2.3 mm $\times$ 0.5 mm.

Figures 3(c) and 3(d) show second- and third-order Bragg diffraction, where $\delta/2\pi$ is 200 and 300 kHz and the intensities are 230 and 340 mW/cm^2, respectively. The efficiency of third-order diffraction was as high as 45%. When the sign of δ is reversed, atoms are diffracted into the opposite direction [Fig. 3(e)]. With longer pulses we have observed up to sixth-order Bragg diffraction with a transfer of 11.9$\hbar k$ (corresponding to a velocity of 0.35 m/s) and an efficiency of about 15%. For such a high-order process we cannot achieve a high efficiency with our detuning because the required pulse length and intensities make the probability of spontaneous emission near unity. Figure 3(f) provides a graphic demonstration of spontaneous emission. The ring pattern results from dipole emission of atoms illuminated by a single traveling wave. Here the direction of observation is along the laser polarization.

In Bragg diffraction the internal state remains unchanged, so the temporal variation of the Zeeman shift due to the rotating bias field of the TOP trap is unimportant. This is true provided the Zeeman shifts are small compared to Δ, as in our case. We can therefore use Bragg diffraction in the trap to study the motion of trapped atoms. In Fig. 4 we create a train of orbiting wave packets. In the adiabatically expanded TOP trap we irradiate
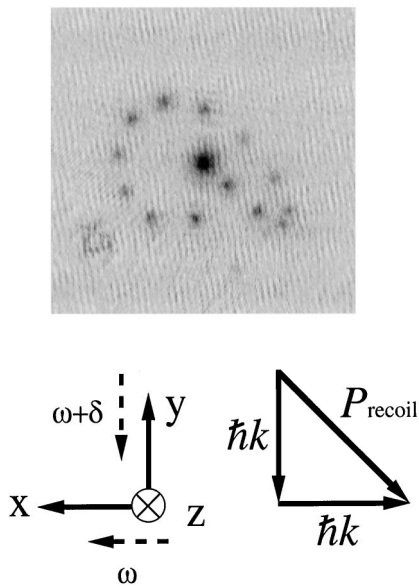
FIG. 4. Optical depth image of the condensate after 13 Bragg pulses while in the TOP trap. Here x is the quadrupole axis and z is the direction of gravity. The TOP bias field rotates in the x-z plane. The Bragg diffraction beams propagate along the x and $-y$ directions. The width of the field of view is 1.2 mm $\times$ 1.2 mm.

the BEC with a series of 13 pulses, each separated by 5 ms. The 13 wave packets and the remaining condensate are then imaged with a single probe pulse. To generate many wave packets without substantially depleting the condensate, we decrease the pulse duration to 20 μs, reducing the diffraction efficiency. Here the crossing angle of the laser beams is 90° and $\delta/2\pi = 50$ kHz to satisfy the first-order Bragg condition. Since the trap potential is noncentral, atoms launched along a direction (45° with respect to x and y in this case) other than a principal axis will not execute closed orbits, as seen in Fig. 4. The orbit of the wave packets agrees with the classical equations of motion in our harmonic trap with its incommensurate frequencies [24].

In summary, we have demonstrated coherent Bragg diffraction of Bose-Einstein condensed sodium atoms. This technique, demonstrated both with and without the trapping fields, can be used to manipulate condensates and to study fundamental aspects of their properties. For example, it is possible to measure the coherence time of a BEC. Atoms may be launched along a principal axis, so that the diffracted wave packet will return to the condensate after an integral number of half-oscillation periods. The application of a second Bragg pulse when the diffracted wave packet and the original BEC overlap would produce interference, allowing a coherence time measurement in the trap. If, instead, the trap is switched off, the phase of the condensate will start to evolve because the mean-field repulsion is no longer balanced by the trap potential. Successive application of Bragg pulses could probe the temporal evolution of the condensate phase (here one would apply the second pulse before the first wave packet leaves the region of the condensate). Experiments on nonlinear atom optics are also possible using these techniques. For example, four-wave mixing of matter waves should occur due to the nonlinearity arising from atom-atom interactions [25,26]. Bragg diffraction can create the three different momentum states necessary to produce a fourth momentum component. High-order Bragg diffraction is ideal as an output coupler for an atom laser. Output coupling with momentum transfer should produce an extremely well collimated beam of coherent atoms.

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