Output Coupler for Bose-Einstein Condensed Atoms

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We have demonstrated an output coupler for Bose condensed atoms in a magnetic trap. Short pulses of rf radiation were used to create Bose condensates in a superposition of trapped and untrapped hyperfine states. The fraction of out-coupled atoms was adjusted between 0% and 100% by varying the amplitude of the rf radiation. This configuration produces output pulses of coherent atoms and can be regarded as a pulsed "atom laser." [S0031-9007(96)02255-7]

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The recent realization of Bose-Einstein condensation (BEC) in atomic gases [1–4] provides samples of atoms with a macroscopic population in the ground state of the system. This population forms a coherent matter wave and is described by a macroscopic wave function, which is the solution of the nonlinear Schrödinger equation [5]. Recently, several papers have discussed the analogies between coherent matter waves and coherent photons and have worked out the theory for an "atom laser" [6–10]. An atom trap is the atomic analog to an optical cavity, and evaporative cooling into the Bose-Einstein phase transition represents a gain mechanism through which bosonic atoms accumulate in a single mode of the trap. A condensate released from the trap propagates according to a "single-mode" wave equation [11–13]. Theoretical discussions of the atom laser have considered the case in which atoms are fed into and coupled out of the "lasing mode" continuously [6–10]. In comparison to the photon case, the coherence of the atom laser is complicated by the dispersion of particles with finite rest mass and the presence of collisions [6–8].

In this paper, we do not deal with the subtle issue of coherence, but demonstrate methods to couple a Bose condensate out of a magnetic trap. The rf-induced output mechanisms discussed here provide a controlled, nondissipative way of coupling the trapped Bose condensate to propagating modes. Gravitational acceleration gives the output a distinct direction. Output coupling realizes a crucial element in turning a Bose condensate into an atom laser [14], although the sudden release of a condensate by switching off the trapping potential can already be regarded as a crude form of such a laser. The creation of a controlled, quasicontinuous output from a Bose condensate would allow one to monitor the phase of a condensate and study phase diffusion and other decoherence processes, as recently suggested by several authors [12,15–20].

Our output coupling scheme is most easily discussed for the case of a two-level system consisting of state $|1\rangle$, a magnetically trapped state, and state $|2\rangle$, an untrapped state. Consider a Bose condensate of atoms in state $|1\rangle$. A resonant rf pulse of duration τ couples states $|1\rangle$ and $|2\rangle$ with the matrix element $\hbar\omega_R/2$, where ω_R is the Rabi frequency. State $|1\rangle$ evolves into the superposition $t|1\rangle + r|2\rangle$ with $t = \cos(\omega_R\tau/2)$ and $r = \sin(\omega_R\tau/2)$. The N-particle wave function of the Bose condensate is then given by the symmetric product

$$(t|1\rangle + r|2\rangle)^N = \sum_{n=0}^{N} \sqrt{\frac{N!}{n!\,(N-n)!}}\, t^{N-n} r^n |N-n, n\rangle, \tag{1}$$

where $|N-n, n\rangle$ is a state with $N-n$ trapped and n untrapped atoms. The fraction of atoms coupled out of the condensate oscillates with the single-particle Rabi frequency ω_R as $\langle n\rangle/N = |r|^2 = \sin^2(\omega_R\tau/2)$.

The superposition state in Eq. (1) can also be achieved by sweeping the rf through resonance. The populations of trapped and untrapped states can be controlled by adjusting the sweep parameters from diabatic (no transfer of population) to adiabatic (complete transfer by adiabatic passage). In the case of a sweep with constant rate $d\omega_{\mathrm{rf}}/dt$, one has $|r|^2 = 1 - e^{-2\pi\Gamma}$ and $|t|^2 = e^{-2\pi\Gamma}$, with the Landau-Zener parameter $\Gamma = \omega_R^2(4d\omega_{\mathrm{rf}}/dt)^{-1}$ [21]. The sweep scheme has the advantage that it is not affected by small drifts in the resonance frequency, for example due to fluctuations of the magnetic field in the trap center. Furthermore, a complete transfer to the untrapped state $|2\rangle$ is insensitive to the rf amplitude as long as the sweep is adiabatic.

Such an output coupler for a two-state system could be realized with alkali atoms by using an rf transition which couples a trapped state in one hyperfine level to an untrapped state in the other hyperfine level. Instead, for experimental simplicity, we realized an output coupler for a three-state (spin 1) system by inducing lower frequency rf transitions within the $F = 1$ ground state hyperfine manifold of sodium. In such a system, the rf radiation couples the magnetically trapped $m_F = -1$ state to the untrapped $m_F = 0$ state, which is in turn coupled to the expelled $m_F = 1$ state; at low magnetic fields, the resonance frequencies for these transitions are the same. Both output coupling schemes discussed above are readily generalized to a three-state system. A short resonant rf pulse of duration τ prepares the atoms in a superposition state

$a_{-1}|m_F = -1\rangle + a_0|m_F = 0\rangle + a_1|m_F = 1\rangle$ with the coefficients $a_{-1} = \cos^2(\omega_R\tau/2)$, $a_0 = (i/\sqrt{2})\sin\omega_R\tau$, and $a_1 = -\sin^2(\omega_R\tau/2)$. ω_R parametrizes the coupling matrix element which is $\hbar\omega_R/\sqrt{2}$. The coefficients for a nonadiabatic rf sweep are obtained by solving a three-state Landau-Zener model numerically, and are approximated to better than 0.1% by [22]

$$\begin{aligned} |a_{-1}|^2 &= e^{-2\pi\Gamma}, \\ |a_0|^2 &= 2e^{-\pi\Gamma}(1 - e^{-\pi\Gamma}), \\ |a_1|^2 &= (1 - e^{-\pi\Gamma})^2, \end{aligned} \qquad (2)$$

with $\Gamma = \omega_R^2/(2d\omega_{\mathrm{rf}}/dt)$. These results are also valid for interacting atoms as long as the total wave function factorizes into position-dependent and spin-dependent parts.

Since the atoms are trapped in an inhomogeneous magnetic field, the rf resonance frequency varies over the spatial extent of the condensate. However, by using a sufficiently short pulse duration τ or a fast sweep rate $d\omega_{\mathrm{rf}}/dt$, the inhomogeneous width can be neglected, and the coupling is position independent. Otherwise, one would produce spatially dependent superposition states [23].

The rf output coupler was demonstrated for a Bose condensate of sodium atoms, produced in the same way as in our previous work [3]. Briefly, sodium atoms were optically cooled and trapped and then transferred into a magnetic trap, where they were further cooled by rf-induced evaporation [24]. Evaporative cooling was extended well below the transition temperature to obtain a condensate without a discernible normal fraction. Every 30 seconds, a condensate containing 5×10^6 sodium atoms in the $F = 1, m_F = -1$ ground state was produced. The condensate was confined in a cloverleaf magnetic trap with the trapping potential determined by the axial curvature of the magnetic field $B'' = 125\ \mathrm{G/cm^2}$, the radial gradient $B' = 150\ \mathrm{G/cm}$, and the bias field B_0, which was set to 1.1 G for the rf pulse output coupler and to about 0.4 G for coupling induced by an rf sweep. The rf magnetic field was linearly polarized and orthogonal to the static magnetic field in the trap center.

Implementation of the output coupler using a resonant rf pulse required a high degree of bias field stability. Shifts in the resonance frequency from drifts of the bias field between cooling cycles had to be much smaller than the inverse duration of the rf pulse. The minimum pulse duration was approximately 5 μs due to limitations of the available rf power. The small bias field B_0 in the center of the trap was achieved by canceling the large magnetic field due to the axial curvature coils with an "antibias" field produced by a Helmholtz coil pair. High stability of B_0 was accomplished by operating these coils in series with a single current-stabilized power supply. It should be noted that evaporative cooling removes atoms with an energy of $10k_BT$ (which corresponds to 300 kHz at the onset of BEC) and is consequently much less sensitive to bias field drifts.

As discussed above, the rf pulse couples a fraction of initially trapped condensate atoms into the untrapped $F = 1, m_F = 0, 1$ states. Atoms with $m_F = 1$ are strong field seekers and are accelerated away from the trap center, while the atoms in the $m_F = 0$ state freely expand and eventually experience a weak repulsive potential due to quadratic Zeeman shifts. In addition, both pulses are accelerated downward due to gravity. The time evolution of the $m_F = 0$ pulse in the magnetic trap is shown in Fig. 1. The output pulse of atoms in the "repelled" $m_F = 1$ state was observed only in the first 3 ms after the rf interaction.

The different propagations of the two output pulses in the magnetic field allowed their separate observation by absorption imaging, either in the $F = 1$ level using near-resonant $F = 1 \rightarrow F' = 2$ probe light, or by optically pumping the atoms into the $F = 2, m_F = 2$ state and using the $F = 2 \rightarrow F' = 3$ cycling transition. The number of atoms was obtained by integrating the absorption signal over the image. The magnetic trap was switched

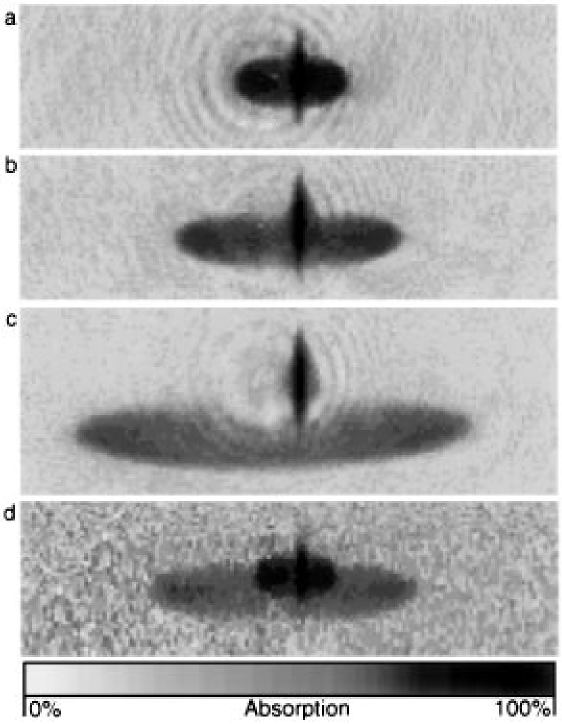

FIG. 1. Absorption images of atoms coupled into the untrapped $F = 1, m_F = 0$ state by a short rf pulse. Images were recorded (a) 14 ms, (b) 20 ms, and (c) 25 ms after the rf pulse using a vertical probe beam. The trapped condensate fraction appears as a thin line in the center of each image. (d) This shows two pulses of $m_F = 0$ atoms coupled out of the same condensate by two consecutive rf pulses spaced 10 ms apart. The image was taken 10 ms after the second rf pulse. It has a noisier background due to lower probe laser power. The width of each image is 3.1 mm.

off at least 1 ms before probing to avoid Zeeman shifts. The trapped fraction of atoms was measured after 40 ms of free ballistic expansion between switch-off of the magnetic trap and probing. Because of gravity, the atoms dropped up to 1 cm between release and detection.

Quantitative measurements were performed using resonant rf pulses of variable amplitude at 757 kHz, which is the Larmor frequency at a bias field $B_0 \approx 1.1$ G. The rf was pulsed on for 5 full cycles (6.6 μs). Figure 2 shows Rabi oscillations in the population of the trapped hyperfine state as a function of the rf field amplitude. The oscillations were found to be in excellent agreement with the predicted $\cos^4(\omega_R \tau/2)$ dependence. The observed Rabi frequency (obtained from the theoretical fit in Fig. 2) agreed with the single-particle Rabi frequency $\omega_R = g\mu_B B_{\mathrm{rf}}/2$ ($B_{\mathrm{rf}}/2$ is the magnetic field amplitude of the rotating wave) to within the accuracy of the rf antenna calibration (estimated to be 20%) [25].

A different variable output coupler for Bose condensed atoms was demonstrated using a nonadiabatic rf sweep. The bias field was set to a value between 0.3 and 0.4 G, corresponding to a resonance frequency between 200 and 300 kHz. The frequency of the rf radiation was chirped from 0 to 500 kHz at a constant rate within 1 ms. The rf magnetic field amplitude B_{rf} was adjusted between 0 and 16 mG, corresponding to a maximum single-particle Rabi frequency ω_R of $2\pi \times 11$ kHz and a Landau-Zener parameter Γ of up to 0.8. Figure 3 shows the fractional populations in the two output pulses versus rf amplitude. The results agree excellently with the solution of the three-state Landau-Zener problem [Eq. (2)]. As before, the Rabi frequency obtained from the fit agreed very well with the one obtained using the antenna calibration.

A third, less controlled method for extracting atoms from a Bose condensate was realized using Majorana flops [26]. These nonadiabatic spin flips were induced by switching the bias field in the trap center to a small negative value. This created two zero-magnetic field points which were swept through the cloud. In the cases of both the Majorana flops and the rf sweep, the coupling is described by a Landau-Zener crossing at zero or at a finite magnetic field, respectively.

In principle, it is possible to continuously couple atoms out of a Bose condensate with resonant rf radiation. The strength of the magnetic trapping field varies by about 10 mG over the spatial extent of the trapped cloud. This variation is mainly due to gravity, which requires a compensating magnetic field gradient of 8 G/cm in the trap center. A controlled cw output coupler therefore requires a very high stability of the magnetic trapping field. It would offer the advantage of coupling out atoms locally, e.g., at the surface of the cloud where the mean-field energy is low.

The spin dynamics of an rf-driven Bose condensate reflects the dynamics of a single atom, as expressed by Eq. (1). The major differences from the classic experiments by Rabi and Ramsey [27] are that 5×10^6 atoms in the same quantum state perform Rabi oscillations synchronously (Fig. 2), and that the inhomogeneous field of a magnetic trap serves as the Stern-Gerlach filter.

We have not demonstrated the coherence of the extracted pulses. However, the rf coupling is nondissipative and the system undergoes a unitary time evolution. A pure quantum state will thus evolve into another pure quantum state. An rf pulse or sweep applied to a condensate with a definite number of atoms creates an entanglement with respect to trapped and untrapped particle numbers [Eq. (1)]. This is analogous to the situation when a Fock state of light passes through a beam splitter. Indeed, the rf output coupler for a two-state system is the atomic equivalent of

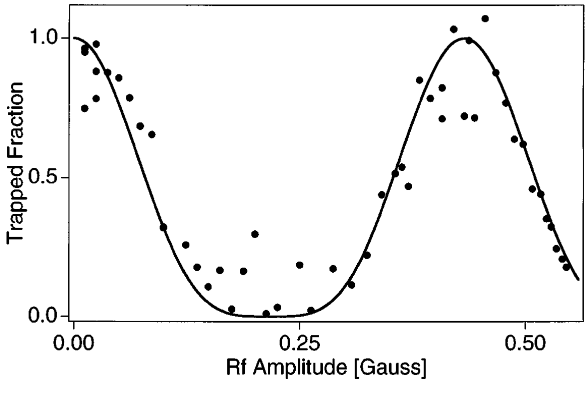

FIG. 2. Rabi oscillations of a Bose condensate. The figure shows the fraction of atoms remaining in the trapped $F = 1, m_F = -1$ state versus the amplitude of the rf pulse. The solid line is the theoretical prediction. The population undergoes Rabi oscillations with the same period as a single particle.

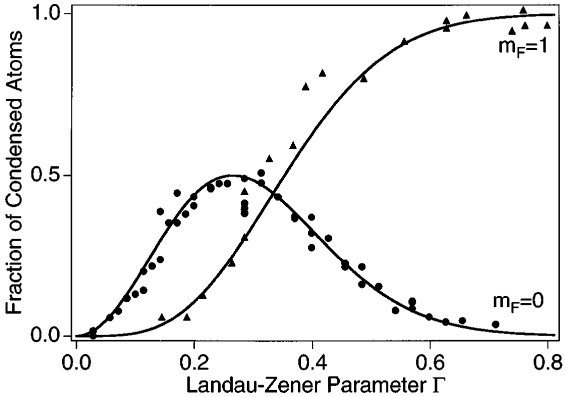

FIG. 3. Realization of an rf output coupler using rf sweeps. The figure shows the fractions of condensate atoms coupled into the untrapped $m_F = 0$ and $m_F = 1$ hyperfine states versus the amplitude of the rf radiation expressed in terms of the Landau-Zener parameter Γ of the rf sweep. The solid line is the theoretical prediction [Eq. (2)]. The maximum $m_F = 0$ fraction was set equal to the theoretical value of 50%, because only relative numbers of $m_F = 0$ atoms were measured.

an optical beam splitter, e.g., a partially reflective mirror. The three-state case is analogous to a beam splitter which has three inputs and three outputs [28]. A condensate which is initially in a coherent state (i.e., has a well-defined phase) remains in such a state after the rf interaction (with an attenuated field amplitude) while the out-coupled pulse of atoms is also in a coherent state. In this case the total N-body wave function factorizes into the trapped condensate and the untrapped pulse.

If the rf coupling scheme is applied to two condensates, observations of the interference between output pulses from each of the condensates can create a definite phase relation between the two trapped condensates through the quantum measurement process. Measurements on subsequent pulses can then be used to verify the initial phase measurement (for a noninteracting condensate) or to observe the phase diffusion due to the mean-field interaction [12,15–20]. For an ideal Bose condensate, repetitive pulses as observed in Fig. 1(d) should be coherent and therefore analogous to the output of a mode-locked laser.

Rf pulses can also be used to manipulate the effective potential of the condensate in two ways. First, when a significant fraction of the atoms is coupled out, the trapped condensate experiences a reduction of the repulsive mean field and should show collective excitations. Similarly, the out-coupled pulse is accelerated both by the repulsion among the extracted atoms and also by the interaction between the output pulse and the trapped condensate. Second, during resonant rf coupling, the effective trapping potential vanishes as the effective magnetic moment of the trapped atoms—that of dressed atoms in an rf field [29]—goes to zero. More generally, by choosing rf pulses with variable detuning, the effective magnetic moment can be varied between zero and its maximum value ($\mu_B/2$ in our case). This allows for a sudden switch-off or reduction of the magnetic trapping potential which is faster than the inductivity-limited shut-off time of electromagnets.

In conclusion, we have demonstrated an rf output coupler for a magnetically confined Bose condensate. This scheme was used to generate pulses of coherent atoms, and realizes a beam splitter for matter waves or a variable output coupler for an atom laser.

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Note added in proof.—Since submitting this paper we have observed the coherence of the condensate in an interference experiment [M. R. Andrews *et al.*, Science (to be published)]. This experiment proved that coherent pulses of atoms can be extracted from a condensate. Therefore a Bose condensate with an output coupler should be regarded as an atom laser.

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