

Bose-Einstein Condensates near a Microfabricated Surface

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Magnetically and optically confined Bose-Einstein condensates were studied near a microfabricated surface. Condensate fragmentation observed in microfabricated magnetic traps was not observed in optical dipole traps at the same location. The measured condensate lifetime was ≥ 20 s and independent of the atom-surface separation under both magnetic and optical confinement. Radio-frequency spin-flip transitions driven by technical noise were directly observed for optically confined condensates and could limit the condensate lifetime in microfabricated magnetic traps.

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The manipulation of gaseous Bose-Einstein condensates with magnetic fields produced by wires microfabricated on material surfaces has opened a new frontier in the field of atom optics [1–4]. Magnetic confinement using microfabricated wires is tighter and has higher spatial resolution than is achievable in macroscopic magnetic traps [5–8]. Generally, an important feature of magnetic traps is the excellent thermal isolation between the nanokelvin temperature clouds they confine and the 300 K laboratory environment. However, decreasing the atom-surface separation into the micrometer range has raised concerns that fluctuating surface currents may perturb the atoms [9,10]. While early demonstrations of trapping and guiding laser-cooled thermal atoms with microfabricated devices reported no evidence of deleterious surface effects [11–14], recent studies using samples cooled by forced radio-frequency (rf) evaporation to ≤ 2 μ K have found corrugated potentials [3,15], large heating rates [2,15], and short trap lifetimes [2,15] for atom-surface separations in the 100 μ m regime. The ultimate applicability of microfabricated devices to atom optics depends on the characterization and elimination of such effects.

In this work, we experimentally investigate the behavior of Bose-Einstein condensates near a microfabricated surface. The condensates were confined at the same position relative to the surface by either a microfabricated magnetic trap or an optical dipole trap. Since the two traps operate on different principles and the electromagnetic fields for each have different sources, this study provides a unique examination of the interaction between Bose-Einstein condensates and a microfabricated surface. For example, while condensates confined near the surface in a microfabricated magnetic trap were found to fragment longitudinally [3,15], the clouds remained intact under optical confinement.

Significantly, the measured condensate lifetime in both the microfabricated magnetic trap and the optical dipole trap was ≥ 20 s, an order of magnitude longer than previous results [2,15], and independent of the atom-surface separation. We have directly observed spin-flip transitions driven by rf technical noise for condensates held in the

optical dipole trap. The transition rate increased rapidly with decreasing atom-surface separation implying that distance-dependent losses can occur in magnetic traps where the products of such transitions cannot be directly identified.

Bose-Einstein condensates containing over 10^7 ^{23}Na atoms were created in the $|F=1, m_F=-1\rangle$ state in a macroscopic Ioffe-Pritchard magnetic trap, loaded into the focus of an optical tweezers beam, and transported ≈ 32 cm in 2 s into an auxiliary “science” chamber as described in Ref. [16]. The optical tweezers consisted of ≈ 50 mW of 1064 nm laser light focused to a $1/e^2$ radius of 26 μ m. This resulted in axial and radial trap frequencies $\omega_{\parallel} = 2\pi \times 4$ Hz and $\omega_{\perp} = 2\pi \times 425$ Hz, respectively, and a trap depth of 2.5 μ K. Condensates containing $(2-3) \times 10^6$ atoms arrived 70–500 μ m below the microfabricated structures mounted in the science chamber. The atom-surface separation was varied by angling the optical tweezers axis before translation and was limited to distances ≥ 70 μ m due to the laser beam clipping on the microchip support structures.

In the science chamber, the condensate either remained confined by the optical tweezers or was loaded into a microfabricated Ioffe-Pritchard magnetic trap formed by a Z-shaped wire carrying current I and an external magnetic bias field, B_{\perp} , as described in Ref. [3]. An additional longitudinal bias field, B_{\parallel} , was applied with external coils to adjust the magnetic trap bottom and radial trap frequency. The microfabricated wires were lithographically patterned on a 600 μ m thick silicon substrate mounted on an aluminum block. They were 50 μ m wide and electroplated with copper to a thickness of 10 μ m.

As in previous experiments [3,15], condensates confined near the surface in the microfabricated magnetic trap were observed to fragment longitudinally [Fig. 1(a)]. The condensate density depletions appeared in the same longitudinal position relative to the surface on each realization of the experiment, and more fragments formed as the atoms came closer to the microchip [3]. In contrast, condensates confined optically at the same location were not observed to fragment [Fig. 1(b)]. The same

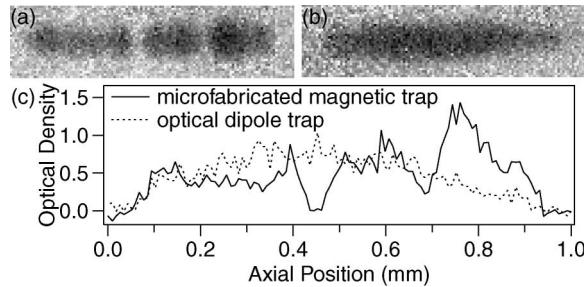


FIG. 1. Fragmentation of Bose-Einstein condensates. Transverse absorption images after 10 ms ballistic expansion of condensates containing $\approx 10^6$ atoms after holding at a distance of $85 \mu\text{m}$ from the microfabricated surface for 15 s in the (a) microfabricated magnetic trap and (b) optical dipole trap. (c) Radially averaged optical density vs axial position for condensates shown above. Longitudinal fragmentation occurred for condensates held in the microfabricated magnetic trap, but not for those confined optically at the same location with the magnetic trap off. The magnetic trap was operated with $I = 130 \text{ mA}$, $B_{\perp} = 3.2 \text{ G}$, and $B_{\parallel} = 1.4 \text{ G}$ yielding a radial trap frequency $\omega_{\perp} = 2\pi \times 450 \text{ Hz}$. The optical dipole trap had a radial trap frequency $\omega_{\perp} = 2\pi \times 425 \text{ Hz}$ and was operated with $B_{\parallel} = 1.8 \text{ G}$. For both condensates, the chemical potential was $\mu = k_B \times 120 \text{ nK}$. The absorption imaging light was resonant with the $F = 1 \rightarrow F' = 2$ transition. The field of view in (a) and (b) is $0.25 \text{ mm} \times 1.00 \text{ mm}$.

longitudinal bias field was nominally applied to both magnetically and optically confined condensates so that any surface magnetization effects would perturb the clouds identically. The lack of condensate fragmentation in the optical dipole trap implies that the longitudinal potential corrugations arise due to the presence of current flow in the microfabricated wires, in agreement with conclusions reached elsewhere [17]. Deviations of the current flow from a straight line would lead to such corrugations and could arise due to imperfect microfabrication including variations in the width and thickness of the wire estimated to be 5% of the electroplated thickness, variations in the resistivity of the wire over its cross section, and parasitic conductances to the substrate. Other possible origins of irregular current flow are instabilities at high current density [17].

It is interesting to note that in our earlier work no fragmentation was observed when condensates confined in a macroscopic Z-shaped wire trap were brought within $\approx 10 \mu\text{m}$ of the surface of the wire [16]. The wire was made of copper and had a circular cross section with 1.27 mm diameter. The condensates were loaded into the wire trap $740 \mu\text{m}$ from the surface of the wire and brought closer by lowering the wire current. The experimental parameters upon closest approach were $I = 920 \text{ mA}$ and $B_{\perp} = 2.9 \text{ G}$, yielding estimated axial and radial trap frequencies $\omega_{\parallel} = 2\pi \times 7 \text{ Hz}$ and $\omega_{\perp} = 2\pi \times 78 \text{ Hz}$, respectively [18]. The macroscopic wire trap contained 5×10^5 atoms extended longitudinally over $200 \mu\text{m}$ at a chemical potential $\mu = k_B \times 30 \text{ nK}$. Differ-

ences between the macroscopic and microfabricated wire traps include vastly different fabrication techniques as well as lower current densities in the macroscopic wire.

Confined atoms are sensitive to noise at their trap frequency and Zeeman splitting frequency [9,10]. In this work, typical radial trap frequencies were $\approx 500 \text{ Hz}$ while Zeeman splitting frequencies were $\approx 1 \text{ MHz}$. Noise at the trap frequency leads to heating and subsequent trap loss after the atoms acquire an energy greater than the trap depth. For atoms confined in a Ioffe-Pritchard magnetic trap, radial magnetic bias field fluctuations cause radial trap-center fluctuations. The amplitude of such trap-center fluctuations is independent of the longitudinal bias field. However, for optically confined atoms, only fluctuating radial magnetic field *gradients* cause radial trap-center fluctuations. The effects of such gradients can be minimized by applying a longitudinal bias field that adds in quadrature with the fluctuating radial gradients since it is the gradient of the magnitude of the bias field vector that determines the force on an atom.

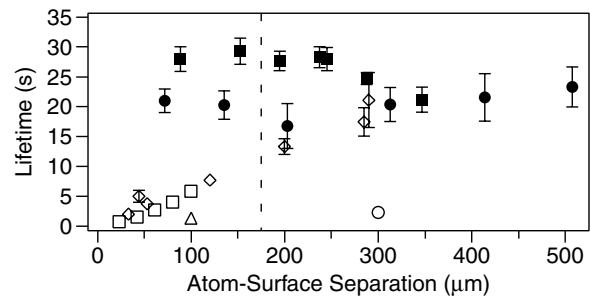


FIG. 2. Lifetime of Bose-Einstein condensates near a microfabricated surface. The $1/e$ lifetime of condensates confined in the microfabricated magnetic trap (solid squares) and optical dipole trap (solid circles) is shown to be independent of distance from the microfabricated surface. Statistical error bars are included. Additionally, excitations created while transferring the condensate from the optical tweezers into the microfabricated magnetic trap caused fluctuations in the measured magnetic trap lifetime, indicated by the scatter in the data. I and B_{\perp} were varied with distance to maintain the radial magnetic trap frequency at $\omega_{\perp} = 2\pi \times 450 \text{ Hz}$ with $B_{\parallel} = 1.4 \text{ G}$. The vertical line indicates the onset of longitudinal condensate fragmentation in the magnetic trap. In the optical dipole trap, the condensate was held directly below the microfabricated wire used to form the magnetic trap with $B_{\parallel} = 1.8 \text{ G}$. No external connections were made to the microchip. The optical dipole trap had axial and radial trap frequencies $\omega_z = 2\pi \times 4 \text{ Hz}$ and $\omega_{\perp} = 2\pi \times 425 \text{ Hz}$, respectively. Only atoms remaining in the $|1, -1\rangle$ state were resonant with the absorption imaging light. For comparison, the distance dependence of thermal cloud lifetimes measured in Ref. [15] is shown for atoms confined magnetically by a microstructure (open squares) and copper wire (open diamonds). Error bars smaller than the symbol size are not included. Also, magnetically confined condensate lifetimes reported in Ref. [2] (open triangle) and Ref. [15] (open circle) are shown for comparison.

Spin-flip transitions driven by rf noise at the atomic Zeeman splitting frequency distribute the atomic population across magnetically confinable and unconfinable states. This causes atom loss for clouds held in magnetic traps. However, all spin states are confined in an optical dipole trap so spin-flip transitions do not lead to loss and the products can be directly observed. Since magnetically and optically confined condensates react differently to noise, whether it is at their trap frequency or the atomic Zeeman splitting frequency, a systematic study of condensate lifetimes in both magnetic and optical traps provides better noise characterization than studies performed in either a magnetic or an optical trap exclusively.

Any atom-surface coupling, regardless of frequency, should manifest itself as a dependence of the condensate lifetime on the atom-surface separation. Figure 2 shows a measurement of the magnetically and optically confined condensate lifetime as a function of the distance from the microfabricated surface. No distance dependence was observed and the measured condensate lifetime was ≥ 20 s, 10 times longer than previous results [2,15]. A distance independent condensate lifetime indicates that atom-surface interactions are unimportant over the 70–500 μm separation range. This is in contrast to results presented in Ref. [15], where a distance-dependent lifetime was observed for thermal atoms magnetically confined near a microfabricated surface. These data are included in Fig. 2 for comparison.

Several experimental details altered the measured condensate lifetime. Excitations created during the microfabricated magnetic trap loading were found to shorten the measured lifetime, and care had to be taken to overlap the optical and magnetic traps during transfer to minimize such excitations. Translating the condensate either towards or away from the microfabricated surface by adiabatically varying I and B_{\perp} to shift the trap center while maintaining a constant radial trap frequency was found to decrease the condensate lifetime. This presumably resulted from excitations induced by irregular current changes due to technical limitations in controlling the power supplies connected to the microchip. As a result, microfabricated magnetic trap lifetime data are presented only for atom-surface separations ≥ 70 μm , where the atoms were loaded into their final position directly from the optical tweezers. Occasionally, heating was observed for atoms in both the microfabricated magnetic trap and optical dipole trap due to technical noise at the trap frequency, even with care taken to eliminate ground loops and minimize cable lengths [19]. Connecting a 10 mF capacitor in parallel with the 2 Ω microfabricated wire ($1/RC = 2\pi \times 8$ Hz) eliminated such effects. Thereafter, applying rf power to the microchip at a frequency chosen to limit the trap depth for magnetically confined atoms did not consistently alter the condensate lifetime.

The distance independent condensate lifetime presented in Fig. 2 indicates that our experiment is not

currently limited by the proximity of the microfabricated surface. However, we have observed spin-flip transitions driven by rf noise in the microfabricated wires. Figure 3 shows the behavior of condensates confined optically directly beneath the microfabricated wire used for magnetic trapping. Condensate atoms initially in the $|1, -1\rangle$ state [Fig. 3(a)] were found to make transitions to other magnetic sublevels [Fig. 3(b)]. Such transitions would act as a loss mechanism for magnetically confined clouds. The transition rate was found to decrease as the square of the atom-surface separation distance, d . Since the magnetic field of a straight wire decays as $1/d$, and the power scales as the square of the field, the $1/d^2$ dependence of the spin-flip transition rate is expected for atoms in the near field ($d \ll \lambda$) of the wire, where $\lambda \approx 300$ m is the wavelength of ≈ 1 MHz radiation.

The transition rate vs distance data presented in Fig. 3(c) were taken with all connections necessary to run the microfabricated magnetic trap made to the microchip, but with no current flowing in the microfabricated wires. The atoms were exposed to a longitudinal bias field $B_{\parallel} = 1.8$ G to simulate the field configuration in the microfabricated magnetic trap. This also maximized their

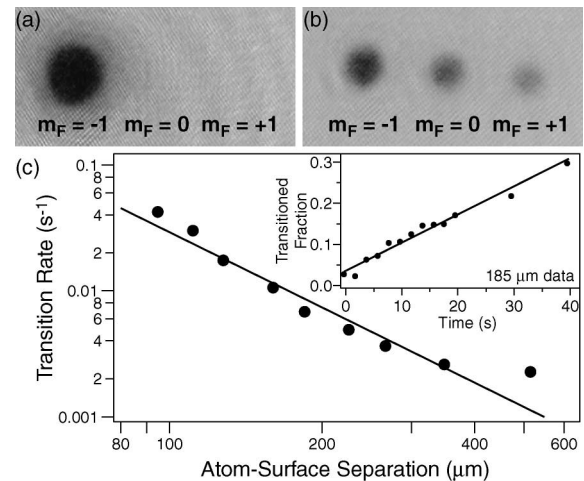


FIG. 3. Spin-flip transitions driven by radio-frequency technical noise. Axial absorption images after 22 ms ballistic expansion of condensates held in the optical dipole trap at a distance of 185 μm from the microfabricated surface for (a) 0 s and (b) 40 s. A magnetic field gradient was applied during ballistic expansion to separate the different spin states. (c) Spin-flip transition rate, Γ , vs distance, d , from the microfabricated surface on a log-log scale. A line $\Gamma \propto 1/d^2$ is provided as a guide. The inset shows the fraction of the total atoms in the $m_F = 0$ state with the transition rate being defined as the initial slope of the data (before any atoms in the $m_F = +1$ state were detected). The absorption imaging light was resonant with the $F = 2 \rightarrow F' = 3$ transition. The atoms were optically pumped into the $F = 2$ hyperfine level with a pulse resonant with the $F = 1 \rightarrow F' = 2$ transition. This provided equal imaging sensitivity to each magnetic sublevel. The field of view in (a) and (b) is 1.0 mm \times 2.0 mm.

sensitivity to fluctuating fields generated by wire currents since rf transitions are more favorable for magnetic fields oscillating orthogonal to a static bias field. Spin-flip transitions were suppressed by exposing the optically confined atoms to an orthogonal bias field, B_{\perp} .

The rf driven spin-flip transition rate depended strongly on experimental details, suggesting that antenna effects coupled rf noise into the system. The rate was measured to be of order 100 times higher if care was not taken to carefully eliminate ground loops and use minimal cable lengths [19]. Also, with no connections to the microchip, spin-flip transitions were not detectable for condensates held up to 60 s. The spin-flip rate presented in Fig. 3(c) became comparable to the measured condensate decay rate displayed in Fig. 2 for atom-surface separations $< 100 \mu\text{m}$. Thus, extending long condensate lifetimes much closer to the surface will require further rf shielding and/or filtering.

In conclusion, we have studied the behavior of Bose-Einstein condensates near a microfabricated surface. Condensates found to fragment while held in a microfabricated magnetic trap were observed to remain intact while held at the same position relative to the microchip in an optical dipole trap. A possible explanation is that deviations of the current path from a straight line give rise to corrugations in the longitudinal potential. The origins of such current path deviations are under investigation. Furthermore, our work demonstrates magnetically and optically confined condensate lifetimes ≥ 20 s at distances $\geq 70 \mu\text{m}$ from a microfabricated surface. The lifetime was measured to be independent of the atom-surface separation and 10 times longer than results obtained elsewhere at comparable distances. Spin-flip transitions driven by rf technical noise were directly observed for condensates held in an optical dipole trap; however, we found no evidence for fundamental, thermally induced noise driven processes above the level of those attributed to technical noise. Our results demonstrate the extreme sensitivity of Bose-Einstein condensates to small static and dynamic electromagnetic fields. This sensitivity provides a challenge for realizing microfabricated atom-optical devices, but it also emphasizes the potential for developing new detector and instrumentation technology.

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Note added.—Recently, we have observed condensate fragmentation near conductors $50 \mu\text{m}$ wide and evaporated with gold to a thickness of $1.25 \mu\text{m}$. This shows that the fragmentation phenomena are not limited to copper

conductors, in agreement with conclusions reached elsewhere [20]. Also, Ref. [20] reports magnetic trap lifetimes limited by thermally induced spin flips.

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