

## All-Optical Realization of an Atom Laser

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We demonstrate an atom laser using all-optical techniques. A Bose-Einstein condensate of rubidium atoms is created by direct evaporative cooling in a quasistatic dipole trap realized with a single, tightly focused CO<sub>2</sub>-laser beam. An applied magnetic field gradient allows the formation of the condensate in a field-insensitive  $m_F = 0$  spin projection only, which suppresses fluctuations of the chemical potential from stray magnetic fields. A collimated and monoenergetic beam of atoms is extracted from the Bose-Einstein condensate by continuously lowering the dipole trapping potential in a controlled way to form a novel type of atom laser.

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The development of optical lasers has revolutionized the field of light optics. To date, evaporative cooling of bosonic atoms in traps has allowed for the production of Bose-Einstein condensates [1]. In magnetic traps, atoms from the macroscopically populated ground state have been extracted with an applied radio frequency forming a coherent beam, and this source is commonly referred to as an atom laser [2–5]. Atom lasers realized so far have all involved magnetic field-sensitive states, where a stray magnetic field  $\Delta B$  causes a shift of the chemical potential of order  $\mu_B \Delta B / k_B$  ( $\cong \Delta B \times 67$  nK/mG). It has been demonstrated that, by using magnetic shielding, a quasi-continuous atom laser beam can nevertheless be successfully generated in a typical, magnetically noisy laboratory environment [5]. On the other hand, the extremely successful development of atomic frequency standards and atom interferometers has demonstrated the benefit of using first-order field-insensitive ( $m_F = 0$ ) Zeeman states [6]. While atoms in such states cannot be trapped in magnetic traps, optical dipole force traps can confine atoms in all spin states. Successful evaporative cooling to Bose-Einstein condensation has recently been demonstrated in dipole force traps [7,8].

We report here on the realization of a quantum degenerate gas in a trap confining atoms in field-insensitive Zeeman states alone. The remaining magnetic field sensitivity of the chemical potential is  $0.014$  pK/(mG)<sup>2</sup> and determined only by the quadratic Zeeman effect. We have extracted the condensed atoms into a collimated, monochromatic beam to form an all-optical atom laser. Our experiment is based on direct evaporative cooling of rubidium atoms in a strongly focused CO<sub>2</sub>-laser dipole trap. The use of a single running wave allows for very stable operation of the condensate production. Note that previous experiments creating quantum degeneracy in dipole traps have either required the use of a more alignment-sensitive crossed dipole trap geometry [7] or Feshbach resonances [8,9] to enhance the collisional rate. In our experiment, a magnetic field gradient induces a force that is larger than the confining force

along the weakly confining axis of the CO<sub>2</sub>-laser beam and, thus, effectively removes all atoms in field-sensitive states during the final stage of the evaporation. With no applied field gradient, a spinor condensate with 12 000 atoms distributed among the  $m_F = -1, 0,$  and  $1$  states is produced. When the gradient is activated, typically 7000 atoms condense into the  $m_F = 0$  component alone. We do not observe losses from spin-changing collisions. Finally, by smoothly ramping down the trapping potential we have coherently extracted atoms from the condensate to form a well collimated atom laser beam. The coupling rate can be varied by adjusting the ramp time. The duration of the output is limited only by the number of trapped atoms.

Studies of cooling atoms in optical dipole traps towards high phase space densities were first carried out by the Stanford group with a YAG-laser trap [10]. Researchers have since then investigated both the limits of laser and evaporative cooling in optical traps [11]. Friebe *et al.* noted that in quasistatic dipole traps, as can be realized with a CO<sub>2</sub> laser, polarization gradient cooling alone can yield surprisingly high phase space densities [12]. In an impressive experiment, Chapman and co-workers then realized a Bose-Einstein condensate by evaporative cooling of atoms in a crossed CO<sub>2</sub>-laser trap [7].

Our Bose-Einstein condensate is produced in a single, tightly focused beam ( $\lambda \approx 10.6$   $\mu\text{m}$ ) derived from a CO<sub>2</sub> laser. For this midinfrared radiation, the trapping potential for atoms is well approximated by  $V = -\alpha_s/2|E|^2$ , where  $E$  denotes the laser electric field and  $\alpha_s$  the static atomic polarizability. The trapping potential is confining for all Zeeman levels of the electronic ground state. Evaporative cooling in an optical trap is most straightforwardly achieved by lowering the trapping potential [10]. The energetically highest atoms escape the trap, and the remaining atoms rethermalize to a Maxwellian distribution with lower temperature. Mandatory for the success of this cooling technique is a sufficiently high elastic collision rate  $\Gamma_s \approx n\nu\sigma$ , being responsible for rethermalization, throughout the evaporation ramp. Let

us discuss the scaling of this rate on experimental parameters. Assuming that the atoms are well localized in the trap, the potential is harmonic and the average potential energy per dimension is  $k_B T/2 = \frac{m}{2} (2\pi\nu_i)^2 \langle x_i^2 \rangle$ , where  $\nu_i$  denotes the vibrational frequency and  $\langle x_i^2 \rangle$  the mean quadratic spatial extension of the cloud, respectively, along one axis. We infer that the atomic density at a given number of atoms  $N$  scales as  $N\nu_x\nu_y\nu_z/T^{3/2}$ . The vibrational frequency is strongly dependent on the beam focus: along the beam axis  $\nu_z \propto \lambda\sqrt{P}/w_0^3$ , while transversally one obtains  $\nu_{x,y} \propto \sqrt{P}/w_0^2$  as a function of beam power  $P$ , beam waist  $w_0$ , and laser wavelength  $\lambda$ . The collisional rate thus scales as  $\Gamma_s \propto NP^{3/2}/(Tw_0^7)$ . During the course of evaporation, one usually works at a constant ratio of  $\eta = V/k_B T$ , where  $V (\propto P)$  denotes the trap depth so that we arrive at  $\Gamma_s \propto N\sqrt{T}/w_0^7$ . The number of atoms transferred into the dipole trap from the magneto-optical trap (MOT) depends on the beam focus, but a precise model here requires more parameters. For the sake of simplicity, assume that  $N \propto w_0^2$ , so that a  $1/\omega_0^5$  scaling of the collisional rate remains. During the course of the evaporation, the collisional rate in optical traps slows down due to both the reduction in  $T$  and the loss of atoms, as was discussed earlier [7,10,13]. It is demonstrated here that with a comparatively small beam waist Bose-Einstein condensation can be achieved in a running beam geometry. Besides the technical simplicity compared to a crossed beam geometry, the moderate confinement along the beam axis allows one to remove magnetic field-sensitive states during the course of the evaporation by applying comparatively low field gradients.

Our experimental setup is as follows. The near-resonant radiation for cooling and trapping of atoms is generated by two grating stabilized diode lasers. A “cooling laser” is operated with variable (red) detuning from the  $F = 2 \rightarrow F' = 3$  hyperfine component of the rubidium  $D2$  line. Its radiation is amplified by an injection locked diode. We use a “repumping laser” tuned resonantly to the  $F = 1 \rightarrow F' = 2$  hyperfine component. Both optical beams are spatially filtered, expanded to a 20 mm beam diameter, and spatially overlapped before being directed to a vacuum chamber. The total optical power here is 42 mW for the cooling light and 9 mW for the repumping light. A rf-excited  $\text{CO}_2$  laser generates radiation near  $10.6 \mu\text{m}$ . The midinfrared radiation passes an acousto-optic modulator used for controlling the beam intensity and then enters the vacuum chamber through a ZnSe window. An adjustable, spherically corrected lens ( $f = 38.1 \text{ mm}$ ) placed inside the vacuum chamber focuses the beam, which is oriented horizontally, to a waist of  $27 \mu\text{m}$ . A pair of magnetic coils oriented in anti-Helmholtz configuration generates a magnetic quadrupole field with a 10 G/cm field gradient. This field is used both to operate the MOT and to remove field-sensitive Zeeman components during evaporative cooling.

A typical experimental run proceeds as follows. In a 30 s long MOT loading phase, we capture  $6 \times 10^7$  atoms ( $^{87}\text{Rb}$ ) from the thermal background gas emitted by heated rubidium dispensers. During this phase, the cooling laser is operated with a detuning of 18 MHz to the red of the cooling transition. Subsequently, we increase the detuning to 160 MHz and simultaneously decrease the power of the repumping beams to  $\sim 1/100$  of its initial value for a period of 60 ms. By this temporal dark MOT, the atomic cloud is compressed and pumped into the lower hyperfine state as described in more detail in Refs. [10,12]. Throughout this cycle the  $\text{CO}_2$ -laser beam, whose focus overlaps with the MOT center, is left on. Note that, in contrast to more closely resonant dipole traps, the atomic polarizability for a quasistatic field is positive for both the lower and the upper states of the cooling transition. Following the dark-MOT phase, the repumping light is extinguished and after an additional delay of 2 ms also the cooling light. By this time, the atoms are confined in the quasistatic trapping laser field alone. To analyze the trapped atomic cloud at the end of an experimental run, the  $\text{CO}_2$ -laser beam is extinguished and shadow images are recorded after a variable free expansion time.

In initial experiments, we studied the trapping of atoms in the quasistatic dipole potential at full trapping laser power (i.e., with no forced evaporation). For these measurements, the magnetic quadrupole field was switched off by the end of the dark-MOT phase. The trap vibrational frequencies have been measured to be 4.8 kHz transversally and 350 Hz in a direction longitudinal to the beam axis. For very short dipole trapping times, atoms not transferred to this trap have not yet fallen out of the detection region. The earliest that we observe a clean signal of dipole trapped atoms is 70 ms after the end of the dark-MOT phase, at which  $4 \times 10^6$  atoms are detected with a temperature of  $140 \mu\text{K}$ . We observe subsequent trap loss with a faster than vacuum limited rate, which we attribute to initial “natural” evaporation of atoms. At a total dipole trapping time of 100 ms, the number of trapped atoms has decreased to one third and the temperature has reduced to  $90 \mu\text{K}$ . The trap loss then slows down and the trap gradually reaches its vacuum limited lifetime of 12 s. The atomic density at 100 ms dipole trapping time is  $n \approx 1.2 \times 10^{13}/\text{cm}^3$ . We derive an impressive collisional rate of 6.2 kHz and a product  $n\lambda_{\text{dB}}^3 \approx 1.2 \times 10^{-4}$ .

To achieve lower atomic temperatures, forced evaporative cooling is applied. In the dipole trapping phase, the power of the midinfrared beam is ramped down to induce a time-dependent trap potential:  $V(t) \propto (1 + t/\tau)^{-\beta}$ . This function has been designed to maintain a constant value of  $\eta = V/k_B T$  [13]. Optimum cooling was observed when choosing values near  $\tau = 0.45 \text{ s}$  and  $\beta = 1.4$ . We typically use an evaporative cooling time of 7 s during which the dipole trapping beam is reduced to a final

power of 200 mW. Figure 1(a) shows a typical time-of-flight shadow image of the atomic cloud recorded 15 ms after extinguishing the CO<sub>2</sub>-laser beam. For this measurement, the MOT quadrupole field was left on throughout the experimental cycle. We interpret the image as resulting from an almost pure Bose-Einstein condensate of 7000 atoms in the  $F = 1, m_F = 0$  component of the electronic ground state. Atoms in field-sensitive spin projections are removed during evaporation by the field gradient, as the dipole force along the beam axis is comparatively weak [14]. While the trapped atomic cloud is cigar shaped and elongated along the (horizontal) beam axis, the aspect ratio is inverted in the shown time-of-flight image due to the anisotropic release of mean field energy. For comparison, we have also performed measurements with no applied magnetic quadrupole magnetic field during the forced evaporation phase. We then produce a spinor condensate with 12 000 atoms distributed among the  $m_F = -1, 0, 1$  Zeeman components of the  $F = 1$  ground state. Typical data for this measurement are shown in Fig. 1(b), where a separation into clouds with different spin projections is clearly visible.

Subsequent measurements have all been carried out with atoms condensed in the field-insensitive Zeeman component only. We have analyzed cross sections of shadow images taken for different end values of the evaporation ramp. The profiles shown in Figs. 2(a)–2(c) illustrate the formation of the condensate from a thermal cloud in the former to an almost pure Bose-Einstein condensate in the latter image. We deduce a critical temperature  $T_c \approx 220$  nK and a condensate peak density  $1.2 \times 10^{14}/\text{cm}^3$ . The observed condensate lifetime is 5 s and attributed to be mainly limited by three-body collisions. A remarkable issue is that within this lifetime we do not observe transfer of atoms into field-sensitive Zeeman states. We anticipate that spin-changing collisions are suppressed energetically due to

the second order Zeeman effect in the inhomogeneous field [15].

To outcouple the atoms and form an atom laser beam, after creating a condensate we further reduce the trapping laser power in a slow and controlled way. It is clear that the ramp must be smooth enough to minimize condensate excitations. Experimentally, the CO<sub>2</sub>-laser beam power is reduced by applying a 100 ms long linear ramp to the acousto-optic modulator drive. The condensate is outcoupled once the dipole trapping potential  $V(x, y, z) = -\alpha_s/2|E|^2 - mgx$  is approaching the limit of supporting the atomic cloud against gravity. The duration of coherent output is approximately  $\mu/(dV_s/dt)$ , where  $\mu$  denotes the chemical potential and  $dV_s/dt$  the lowering rate of the saddle point of the potential. Figure 3(a) shows a typical image of the outcoupled coherent atom laser beam. We observe an intense, up to 1 mm long, well directed beam of atoms. We expect that the momentum spread is limited by the uncertainty principle only. Experimentally, we can determine the transverse velocity spread along the  $z$  axis to be below our resolution of 0.3 mm/s. The transverse distribution of the (averaged) optical column density can be fitted well when assuming an inverted parabolic profile for the transversal mode of the beam, as shown in Fig. 3(b). This form of trial function is used, since in the Thomas-Fermi limit the condensate density profile images the form of the trapping potential. Of relevance for the transverse mode are the saddle point values over the aperture of the atom laser. The beam is emitted from the (downward directed) side of the condensate. Note that atom lasers based on rf output coupling are often operated in a regime where spin flips into untrapped states are induced in regions interior to the condensate [16]. Compared to such a situation, mean field effects from residing atoms, which can act as a lens for the emitted beam and lead to a transverse interference structure [17], are reduced in the present scheme. We have attempted to

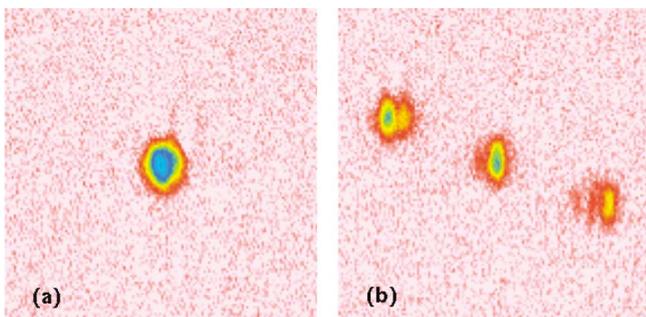


FIG. 1 (color). False-color shadow images of the atomic cloud after 15 ms of free expansion (field of view: 0.33 mm square). (a) Stern-Gerlach magnetic field gradient applied throughout the experiment, so that a pure  $m_F = 0$  condensate is produced. (b) Field gradient activated only during free expansion phase. The three spin projections  $m_F = -1, 0,$  and  $1$  of a spinor condensate are visible as separate clouds.

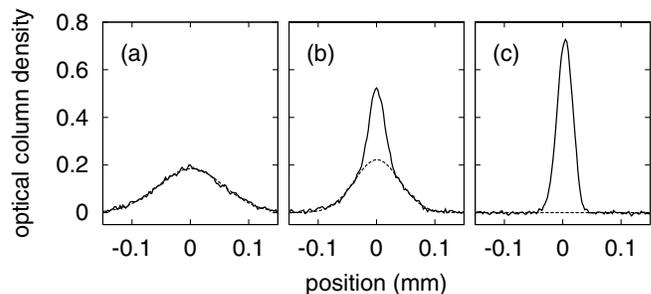


FIG. 2. Vertical cuts through shadow images recorded for pure  $m_F = 0$  ensembles for different final trap laser powers after 15 ms of free expansion. (a) 500 mW: yielding a thermal cloud with  $T \approx 350$  nK, (b) 240 mW: partly condensed ( $T \approx 180$  nK). The dashed line is to guide the eye in distinguishing the broad thermal background from the narrow condensate peak. (c) 200 mW, resulting in an almost pure Bose-Einstein condensate.

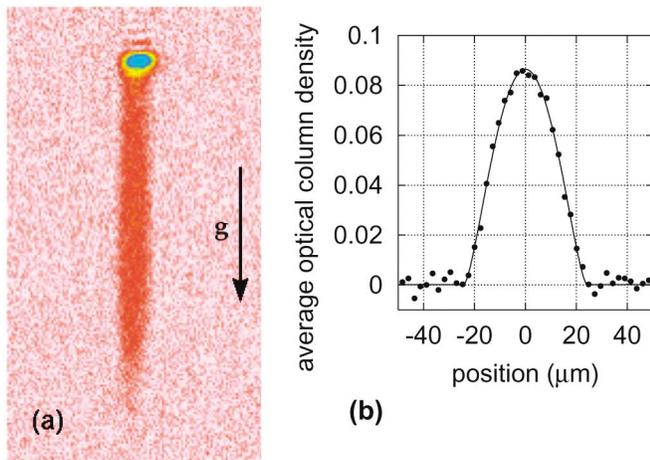


FIG. 3 (color). (a) False-color shadow image of the generated atom laser beam. The field of view comprises 0.28 mm by 0.5 mm. (b) Fitted transverse cut of the image averaged over a 0.19 mm beam length.

estimate the brightness of our atom laser. For the beam shown in Fig. 3(a), the atomic flux is  $8.4 \times 10^5$  atoms/s. If we assume uncertainty limited transverse velocity spreads ( $\Delta v_y \approx 0.33$  mm/s and  $\Delta v_z \approx 0.023$  mm/s) and a Fourier-limited width along the atom laser beam axis ( $\Delta v_x \approx 0.35$  mm/s), we estimate a brightness of  $7 \times 10^{27}$  atoms  $s^2 m^{-5}$ . This is orders of magnitude above results achieved with thermal sources, but a factor of 6 below a similarly derived value for a conventional atom laser given in Ref. [5]. Note that our presently used low power diode cooling lasers yield a comparatively small number of atoms in the MOT, which will be improved in the future.

As fluctuations of the magnetic field cause a shift of the chemical potential via the second order Zeeman effect only [yielding an expected shift  $(\mu_B \Delta B)^2 / (E_{\text{HFS}} k_B)$ ], no magnetic shielding is required for this measurement even in a magnetically noisy environment. It remains important to note that the stability of an atom laser beam is determined by energy fluctuations during the outcoupling process associated with *both* the extracted and the residing atoms. Earlier works, partly realizing output coupling by transfer from field-sensitive into field-insensitive spin projections, thus did experience first-order sensitivity to field fluctuations [2–5]. The output stability of the present scheme is for a smooth ramp limited only by trapping laser intensity fluctuations.

To conclude, we report on the realization of a Bose-Einstein condensate by direct evaporative cooling in a single beam CO<sub>2</sub>-laser dipole trap. The atoms condense into a magnetic field-insensitive state. Our results culminate in the all-optical realization of an atom laser.

For the future, we anticipate that the demonstrated method to produce Bose-condensed atoms opens up ap-

plications in fundamental and applied sciences. The demonstrated technique could furthermore stimulate studies of two-component quantum gases driven by exciting the microwave clock transition between the hyperfine ground states  $F = 1, m_F = 0$  and  $F = 2, m_F = 0$ . It clearly would be of importance to study in detail the stability of different spin projections (and spin mixtures) towards spin-changing collisions. Finally, we foresee that the generated atom laser beam is awaiting fascinating applications in atom optics experiments. Future developments here can allow for improved atom interferometric measurements of gravitation and rotation.

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*Note added.*—After submission of this work, Y. Takasu *et al.* published an approach to producing field-insensitive condensates based on atoms with spin singlet ground states [18].

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