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Bose-Einstein condensation in a quadrupole-Ioffe-configuration trap

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We demonstrate Bose-Einstein condensation of rubidium atoms in a simple low-power magnetic trap. This trap combines the quadrupole with the Ioffe configuration (QUIC trap) and consists of just three coils. Magneto-optically trapped ^{87}Rb atoms are first loaded into the linear trapping potential of a magnetic quadrupole, which is then converted into the parabolic geometry of an Ioffe trap. During this process two spherical quadrupole traps with perpendicular axes merge and the trapped atomic cloud moves close to the magnetic field producing coils, resulting in tight confinement of the atoms while the power dissipation of the trap remains low. The magnetically trapped atoms are cooled to below the phase transition of Bose-Einstein condensation by rf-induced evaporation. [S1050-2947(98)51210-3]

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Since the first experimental demonstrations of Bose-Einstein condensation (BEC) in alkali-metal gases [1–3], the subject has received remarkable attention in the physics community. An increasingly detailed theoretical picture of BEC in dilute gases has emerged over the past years, but the full scope of new experimental possibilities has yet to be revealed. Over the last year a gradually increasing number of experimental groups [4–9] have succeeded in demonstrating BEC, but the exponential growth in the number of BEC experiments that was predicted has not yet come true. Laser-cooled atoms trapped in magneto-optical traps provide the starting point for these BEC experiments. In more than a hundred laboratories all over the world alkali-metal gases are routinely trapped and cooled to temperatures of a few microkelvin using simple vapor cell magneto-optical traps [10]. However, the experimental complexity and difficulties in achieving BEC go much beyond the techniques of laser cooling. Besides requiring an ultrahigh vacuum and a sophisticated timing system, the major challenge lies in designing an adequate and easy-to-use magnetic trap, which forms the core element of each BEC experiment.

The simplest way to magnetically trap atoms is to use the quadrupole field created by two coils with currents in opposite directions. In this configuration the atoms can easily be loaded from a magneto-optical trap into the magnetic trap, since both traps have a common center and share the same symmetry. The magnetic trapping potential $\mu|B(\mathbf{r})|$ is given by the spatially varying magnetic field $B(\mathbf{r})$ and the effective magnetic moment μ of the atom. For an atom in a weak-field-seeking state, the potential in a quadrupole trap grows linearly with distance from the trap center, where the magnetic field is zero. The major shortcoming of quadrupole traps is that cold atoms are removed from the trap due to nonadiabatic spin flips [11,12]. This problem has been solved in time-averaged orbiting potential (TOP) traps [11] and in Ioffe traps [2,13–15], which are both successfully used in current BEC experiments. However, the TOP trap is somewhat limited in its applications due to the low trap depth and the peculiarities arising from the rotating field. On the other hand, Ioffe traps suffer from a difficulty in aligning the center of the magneto-optical trap with the center of the magnetic trap, and Ioffe traps typically dissipate several kilowatts of power, which causes considerable cooling, stabilization, and switching problems.

In this Rapid Communication we report on a type of magnetic trap that incorporates the quadrupole and the Ioffe configuration (QUIC trap). Magneto-optically trapped atoms are first loaded into a magnetic quadrupole trap, which is then converted into a Ioffe-type trap. By spatially separating the centers of the quadrupole and the Ioffe geometry we create a magnetic trap of unprecedented simplicity and efficiency. The QUIC trap consists of merely three coils and dissipates no more than 600 W while operating at a current of only 25 A.

The central feature of the QUIC trap is the transfer of the atoms from a quadrupole into a Ioffe-type trapping geometry. We experimentally study the evolution of the trapped atomic cloud during the change of the potential by taking absorption images at different stages of the transfer. Furthermore, we show that reversing this process leads to a separation into two trapped atomic clouds. We routinely cool the trapped atoms to below the critical temperature of the BEC phase transition by rf-induced evaporation [11,12], whereby the experiment proves to be robust with respect to the precise choice of parameters.

The QUIC trap is shown in Fig. 1. It consists of two identical quadrupole coils and one Ioffe coil. A current I_q through the quadrupole coils produces a spherical quadrupole trap in the center of the two coils. The trap is converted into the Ioffe configuration by turning on the current I_{Ioffe} through the Ioffe coil. In the left column of Fig. 2 the absolute value of the magnetic field along the axis of the Ioffe coil (y axis) is plotted for different currents I_{Ioffe} and a fixed current $I_q = 25$ A. With increasing current I_{Ioffe} the magnetic zero of the quadrupole is shifted towards the Ioffe coil and a second zero appears in the magnetic field, resulting in a second quadrupole trap in the vicinity of the Ioffe coil. When the current I_{Ioffe} approaches 25 A the two spherical quadrupole traps, which have perpendicular axes, merge and an Ioffe trap is formed.

The magnetic field of the Ioffe coil increases the magnetic field gradient produced by the quadrupole coils along the

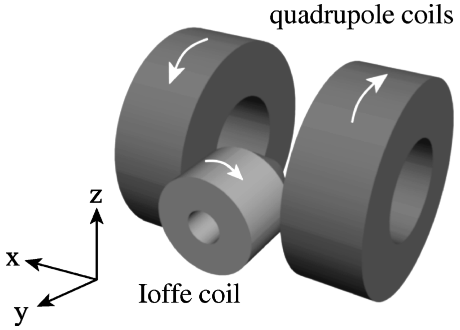

FIG. 1. QUIC trap: The Ioffe coil converts the spherical quadrupole trap into an Ioffe trap with its trap center close to the Ioffe coil. No additional coils are needed to produce a bias field. The arrows indicate the direction of the current flowing through the coils.

vertical axis (z axis) and decreases the field gradient along the symmetry axis (x axis) of the quadrupole coils. The confinement of the atoms along the long axis (y axis) of the Ioffe trap is given by the field curvature produced by the Ioffe coil, which scales as I_{Ioffe}/R^3, with R being the radius of the coil. Since the minimum of the trapping potential is close to the Ioffe coil, a small radius R can be chosen so that the atoms are tightly confined even for a low current I_{Ioffe}. At the minimum of the trapping potential the field of the Ioffe coil and the field of the quadrupole coils almost cancel each other, so that additional bias coils to compress the Ioffe trap in the radial direction are not necessary.

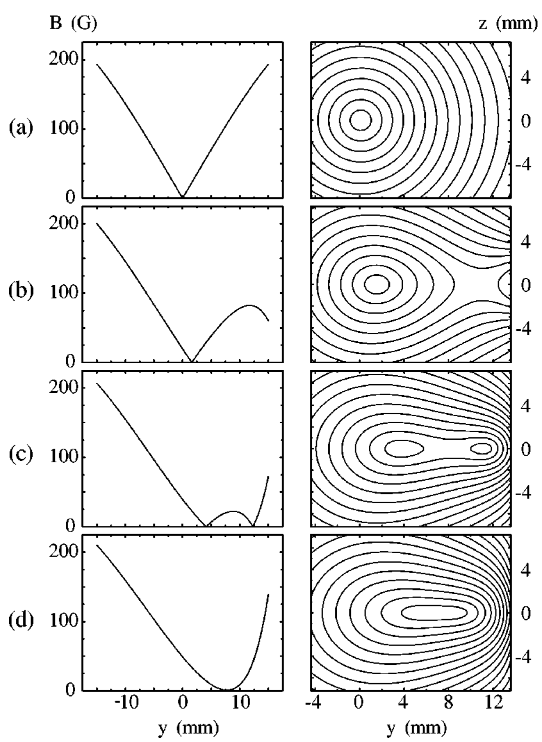

FIG. 2. Absolute values of the magnetic field along the y axis (left column) and in the y-z plane (right column) are shown, calculated for a fixed current of 25 A in the quadrupole coils and (a) 0 A, (b) 10 A, (c) 20 A, and (d) 25 A in the Ioffe coil. Each contour in the right column corresponds to an increase of 15 G in the magnetic field.

Our trap uses quadrupole coils with 180 windings and a conically shaped Ioffe coil with 150 windings [16]. In the Ioffe configuration the trap has a radial gradient of 220 G/cm and the axial curvature is 260 G/cm^2, with a current of 25 A running through all three coils. The offset field of 2 G results in trapping frequencies of $2\pi\times 200$ Hz in the radial and $2\pi\times 20$ Hz in the axial direction, for rubidium atoms in the $|F=2,m_F=2\rangle$ state. Contour plots of the absolute values of the magnetic fields in the y-z plane are shown in the right column of Fig. 2.

Let us now consider a trapped atomic cloud during the conversion process. The atoms will follow the initial shifting and deformation of the trapping potential [Figs. 2(a) and 2(b)] in a reversible manner, as long as the process is carried out slowly enough to be adiabatic. Before the Ioffe configuration is reached, the second quadrupole trap appears in the vicinity of the Ioffe coil [Fig. 2(c)] and the potential takes on the form of a double well. As the trapped atoms start to spill over into the second minimum, the system can no longer be kept in equilibrium. At this point the conversion becomes an irreversible process. When the two quadrupole traps have merged, the barrier between the two potential minima disappears and the atoms experience the harmonic potential of the Ioffe trap [Fig. 2(d)].

Absorption images of the trapped atomic cloud at different stages of the conversion are presented in Fig. 3. The first image [Fig. 3(a)] shows 10^7 atoms at a temperature of 60 ± 10 μK trapped in the magnetic quadrupole, with an axial field gradient of 150 G/cm. Then the current through the Ioffe coil is gradually turned on within 1 s. The second image [Fig. 3(b)] is taken when the trap center has moved by 6 mm towards the Ioffe coil. The deformation of the potential yields an elliptically shaped cloud. Figures 3(c) and 3(d) show how the atoms spill over into the second quadrupole trap. The elongated distribution of the atoms in the Ioffe trap is shown in Fig. 3(e). The initial and final numbers of trapped atoms are deduced from absorption images taken after switching off the trapping potential. We find that to within an accuracy of 10% all the atoms are transferred.

To determine whether the atomic cloud is heated up during the transfer into the Ioffe trap, we reverse the process and convert the Ioffe configuration back into the quadrupole configuration. The atoms are then released from the trap and we take absorption images of the expanding clouds. From these images we deduce a temperature of 60 ± 10 μK, which is the same as the temperature measured initially. We also find that half of the atoms are transferred back into the initial quadrupole trap. This is because the atomic cloud is split into two parts when the Ioffe potential evolves into two quadrupole traps. This is shown in Fig. 3(f). Distributed over both potential minima the atoms now occupy a larger volume than initially. This reflects the fact that the entropy of the system has increased during the conversion. However, the temperature of the atoms has not increased, as no work has been done on the system. We have varied the duration of the conversion between 300 ms and 2 s, which did not significantly change the efficiency of the transfer.

Our experimental setup consists of two magneto-optical traps mounted on top of each other with the trap centers 28 cm apart. The upper system is a standard vapor cell trap that is pumped by a 2l-s^{-1} ion pump. A 5-cm-long tube with an

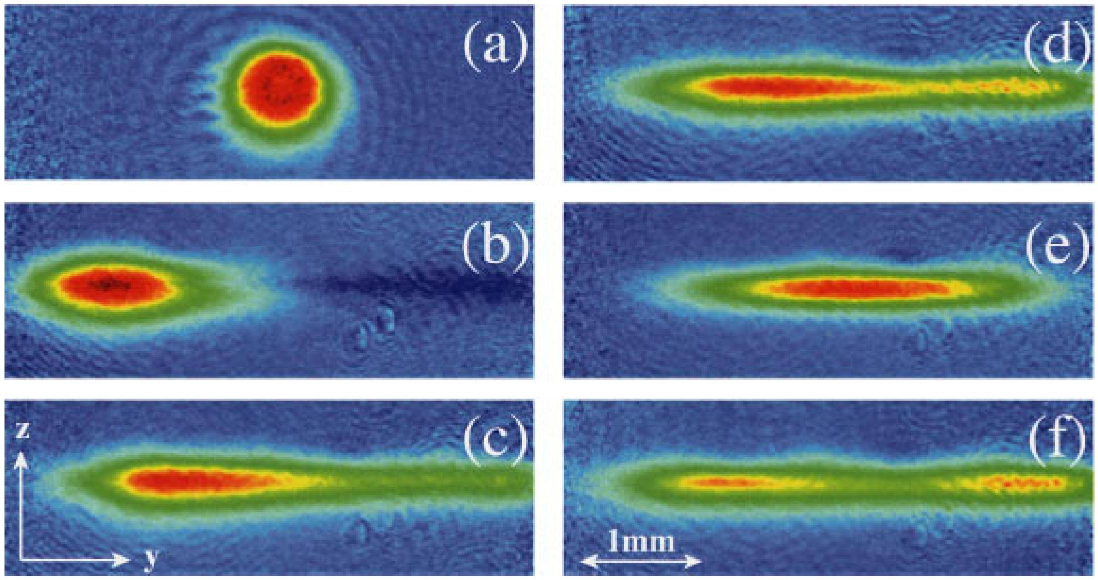

FIG. 3. (Color) Absorption images of the trapped rubidium atoms during the conversion of the quadrupole into the Ioffe configuration (a)–(e). The images are taken after (a) 0 ms, (b) 400 ms, (c) 600 ms, (d) 800 ms, and (e) 1700 ms. Between images (a) and (b) the camera position has been moved by 6 mm to the right. Image (f) shows the atoms distributed over both quadrupole traps that emerge when the current through the Ioffe coil is decreased again.

inner diameter of 5 mm connects the vapor cell to the second magneto-optical trap (UHV-MOT), which is located in an ultra-high-vacuum glass cell. The glass cell is pumped to a pressure of less than 2×10^{-11} mbar using a turbomolecular and a titanium sublimation pump. The glass cell is made of 5-mm-thick optical quality windows and its outer dimensions are 3 cm$\times$3 cm$\times$12 cm, with the long dimension oriented vertically.

Both magneto-optical traps have the same laser-beam geometry, which consists of three pairs of mutually counter-propagating beams. One of the beam axes is oriented along the horizontal x axis and the other two beam axes are oriented along the diagonals in the y-z plane. All laser beams are derived from grating stabilized diode lasers. The laser beams are apertured to a diameter of 12 and 14 mm for the vapor cell and the UHV-MOT, respectively.

The coils of the QUIC trap are put on copper tubes. Each of these tubes is connected to a copper mount that can be cooled with low-pressure tap water. The tubes and the mounts are slit to avoid eddy currents when switching the trapping field on or off. Due to the conical shape of the Ioffe coil the diagonal laser beams are not obstructed. The magnetic quadrupole field for the UHV-MOT is produced by the quadrupole coils of the QUIC trap. The whole trap is built

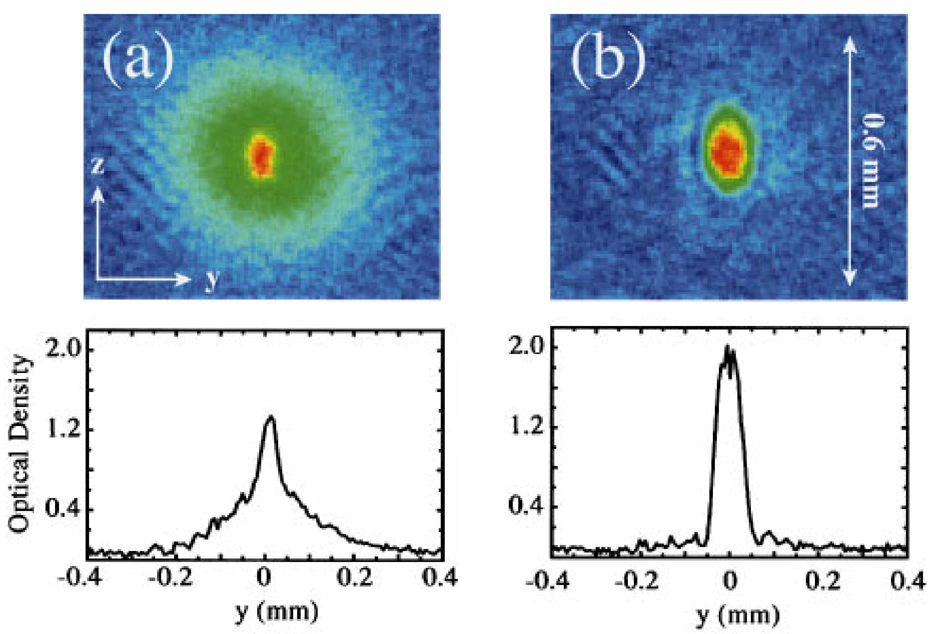

FIG. 4. (Color) Absorption images of the atomic cloud after 17 ms of expansion. (a) Condensate and thermal component at a temperature of 330 nK. (b) Almost pure condensate with 5×10^5 atoms.

into a μ-metal box, which shields it from the earth's magnetic field and reduces environmental magnetic noise.

We use a moving molasses to transfer the atoms from the vapor cell trap into the UHV-MOT [17,18]. By multiply repeating the transfer we typically collect 10^9 atoms within 60 s. Before transferring the magneto-optically trapped atoms into the magnetic quadrupole trap, we compress the trapped atoms by increasing the magnetic-field gradient [19]. Simultaneously the frequency of the trapping beams is detuned by several linewidths. This is followed by 3 ms of polarization gradient cooling to $\approx 40\ \mu$K, with the quadrupole field switched off. Then a 1-G bias field is applied for 1 ms and the atoms are optically pumped into the low-field-seeking $|F=2,m_F=2\rangle$ spin state. The magnetic quadrupole field is rapidly (<1 ms) switched on to an axial gradient of 70 G/cm and the 1-G bias field is turned off 1 ms later. The axial field gradient is increased to 150 G/cm within 2 s before the current through the Ioffe coil is switched on and the trap is converted into an Ioffe trap (see above).

Evaporative cooling of the atoms is performed by rf-induced spin flips. Over a period of 23 s the rf frequency is swept from 30 MHz to a final value of around 1.4 MHz. The cooled cloud is probed by absorption imaging. The cloud is released from the magnetic trap and expands ballistically before it is illuminated for typically 100 μs by a near-resonant probe laser beam, which is directed along the x axis of the trap and tuned to the $F=2\rightarrow F=3$ transition of the D_2 line. Density, temperature, and total number of atoms are derived from the absorption images.

Figure 4 shows images of cooled atomic clouds after 17 ms of ballistic expansion. The data displayed are taken from a set of ten measurements during which we lowered the final value of the rf frequency in 5-kHz steps starting from an initial value of 1.35 MHz. The phase transition occurs at a temperature of $T_c \cong 500$ nK. In another set of measurements we have determined the anisotropy of almost pure condensates for different expansion times (between 5 and 21 ms) and found good absolute agreement with theoretical predictions based on the Gross-Pitaevskii equation [20].

A remarkable feature of the QUIC trap is the stability of the magnetic trapping field. Since all three coils are connected in series (without any resistor parallel to individual coils), the trapping field is completely controlled by the joint current running through the coils. After a thermalization phase of less than 30 min, we observe that the magnetic field at the minimum of the trap varies by less than 2 mG for different runs of the experiment. Due to the μ-metal shielding, short-term fluctuations of the magnetic field are another order of magnitude lower. Long-term drifts in the magnetic field, measured over weeks, are below 10 mG. The high stability of the magnetic field allows precise control of the trapping potential, which is a prerequisite for many conceivable experiments with Bose-Einstein condensates, such as the realization of a Josephson junction for trapped atoms or a cw output coupler for Bose-Einstein condensates.

A major advantage of the QUIC-trap concept is the spatial separation of the MOT and the final magnetic trap. This not only simplifies the coil geometry, but also makes it possible to optimize the MOT and the magnetic trap independently. Much larger trapping beams could be used to collect orders of magnitude more atoms in the MOT than at present, without sacrificing the tight confinement of the magnetic trap. This could be an avenue for future experiments aiming at substantially higher numbers of atoms in the condensate. The separation of the MOT and magnetic trapping region might also prove useful in attempts to produce continuously loaded condensates.

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[1] M. H. Anderson *et al.*, Science **269**, 198 (1995).
[2] C. C. Bradley *et al.*, Phys. Rev. Lett. **75**, 1687 (1995); **78**, 985 (1997).
[3] K. B. Davis *et al.*, Phys. Rev. Lett. **75**, 3969 (1995).
[4] D. J. Han *et al.*, Phys. Rev. A **57**, 4114 (1998).
[5] L. V. Hau *et al.*, Phys. Rev. A **58**, 54 (1998).
[6] B. Anderson and M. Kasevich (unpublished).
[7] U. Ernst *et al.*, Europhys. Lett. **41**, 1 (1998).
[8] W. D. Phillips *et al.* (private communication).
[9] J. Söding *et al.* (unpublished).
[10] C. Monroe *et al.*, Phys. Rev. Lett. **65**, 1571 (1990).
[11] W. Petrich *et al.*, Phys. Rev. Lett. **74**, 3352 (1995).
[12] K. B. Davis *et al.*, Phys. Rev. Lett. **74**, 5202 (1995).
[13] M.-O. Mewes *et al.*, Phys. Rev. Lett. **77**, 416 (1996).
[14] C. J. Myatt *et al.*, Phys. Rev. Lett. **78**, 586 (1997).
[15] J. Söding *et al.*, Phys. Rev. Lett. **80**, 1869 (1998).
[16] The coils have the following dimensions. Quadrupole coils: 34-mm inner diameter, 68-mm outer diameter, and 30-mm length. Ioffe coil: 6-mm inner diameter, 30-mm outer diameter, and 34-mm (20-mm) length. The center to center distance between the quadrupole coils is 66 mm. The distance between the center of the Ioffe coil and the symmetry axis of the quadrupole coils is 34 mm.
[17] M. Kasevich *et al.*, Phys. Rev. Lett. **66**, 2297 (1991).
[18] K. Gibble *et al.*, Phys. Rev. Lett. **75**, 2666 (1995).
[19] W. Petrich *et al.*, J. Opt. Soc. Am. B **11**, 1332 (1994).
[20] Y. Castin and R. Dum, Phys. Rev. Lett. **77**, 5315 (1996).