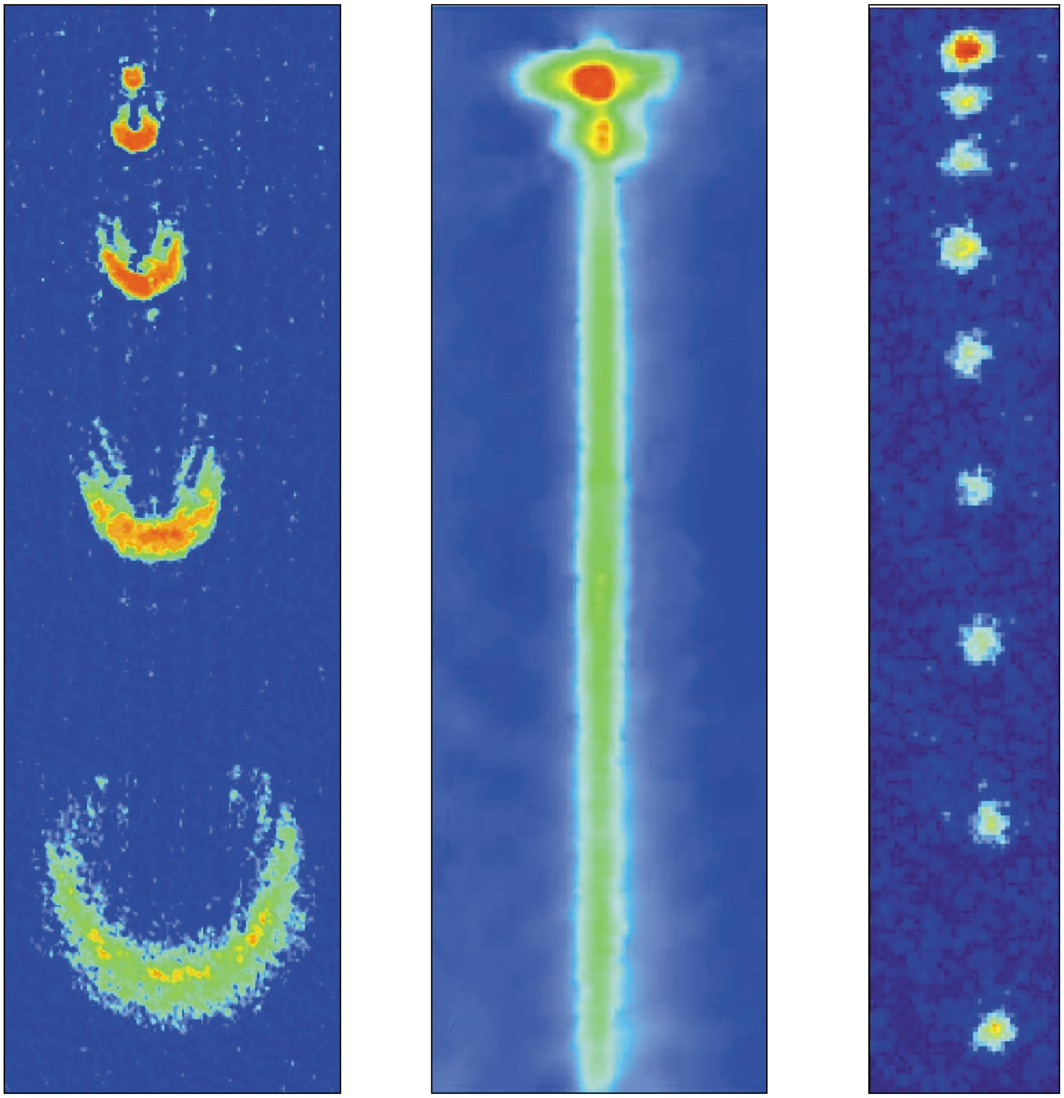

The atom laser

EDWARD W. HAGLEY, LU DENG, WILLIAM D. PHILLIPS, KEITH BURNETT, and CHARLES W. CLARK

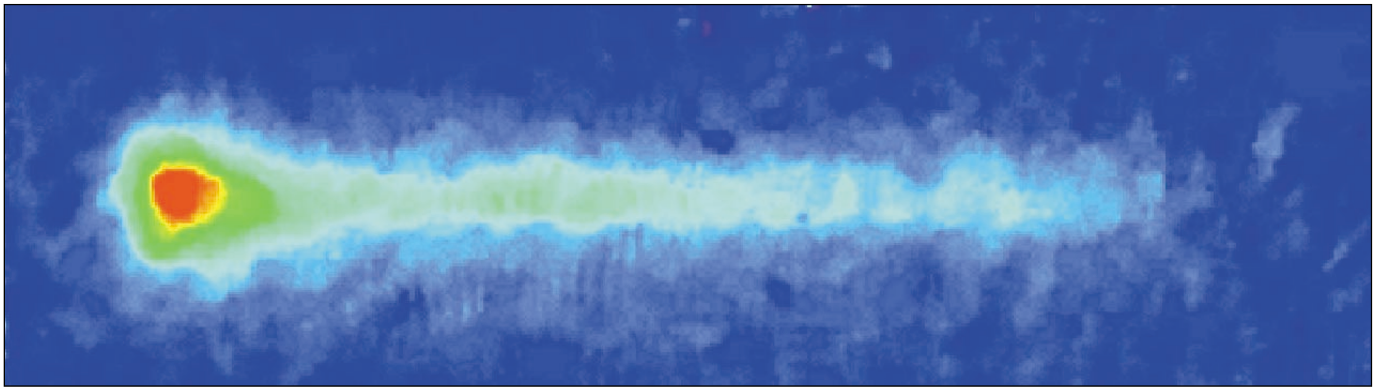

Figure 1. Atom laser beams as produced in various laboratories. Top left to right: MIT: ref. 6; Munich: ref. 7; Yale: ref. 8; Bottom: NIST: ref. 9.

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Optical and matter-wave lasers

Although quantum mechanics is now a century old, its name still evokes the mysterious aspects of modern physics. Even its veteran practitioners regard quantum mechanics, on the one hand, as an enduring scientific mystery: a blend of obvious truths and astonishing surprises. On the other hand, quantum mechanics provides the basis for engineering principles that underpin technologies now as mature and familiar as the incandescent light bulb. In particular, the optical laser, a device whose operation is based on exploitation of the quantum mechanism of stimulated emission identified by Albert Einstein, is now a workhorse of consumer electronics and telecommunications applications. A popular toy and tool, the laser pointer, can be purchased for about the same price as a flashlight.

The spot of a milliwatt laser pointer stands out against the background of a flashlight beam of many watts. While the flashlight spews forth a random stream of photons, no two of which occupy the same mode of the radiation field, the laser concentrates all of its lesser power into a few radiation modes, generating a much greater sensation of brightness. In this article we describe a new device, still in its infancy, which generates a laser-like beam of atoms: large numbers of atoms concentrated into a single quantum state of motion. Our ability to build this device derives from technological breakthroughs in the 1990s, which have made it possible to attain conditions outlined in theory seventy years previously.

Like the optical laser, the atom laser is based on a quantum principle discovered by Einstein. Both of these devices found their practical realization many years after their underlying concept was articulated in theory, with the optical laser enjoying a lead of about forty years over its atomic sister. As far as mastery of techniques is concerned, the level of advancement of atom laser research today may be viewed as roughly comparable to the state of optical laser research in the early 1960s.

At present, there is little prospect that the atom laser will attain the pervasive utility of its optical counterpart. Low-energy atomic beams cannot propagate through any significant distance in air, because of atomic collisions with atmospheric molecules. But the attainment of laser-like action in matter-wave systems offers us the prospect of obtaining the same mastery of atomic beams that the development of the optical laser has provided for the control of light. And whereas today's atom laser systems are bulky, laboratory-table scale objects, comparable in size to the optical laser systems of the early 1960s, we can envisage a future generation of microfabricated systems. These may make it possible to develop "atom-on-a-chip" technology, a platform for integrated matter-wave circuits. Prospective applications of such circuits include gyroscopy, accelerometry, gravimetry, and perhaps quantum logic.

Bose–Einstein condensation

The key enabling technology of today's atom lasers is Bose–Einstein condensation.[1] This phenomenon was discovered by Einstein as a fundamental prediction of the quantum theory of an ideal gas of identical particles. If those particles obey the statistical principle set forth by Bose—which includes the possibility that any number of particles may occupy the same quantum state—then there occurs a remarkable phase transition, which has no counterpart in a classical gas.

As Einstein put it,[2] "for each temperature, there exists a saturation density of the ideal [quantum] gas, such that molecules in excess of this density do not participate in the thermal agitation." Thus, quantum theory predicts that the simplest, unstructured ideal gas, at any temperature, can somehow separate into two components, one of which is divorced from the thermal agitation that pervades the rest of the world.

This fact is no less astonishing to those who have actually witnessed it during the past five years[3] than it was to those who doubted its possibility when it was first proposed in 1924—including perhaps even Einstein himself. It derives from the existence of two characteristic length scales that govern the behavior of an ideal gas: one classical, the other purely quantum mechanical.

The relevant classical length scale of an ideal gas, of atomic density ρ, is the average distance between atoms, $d = \rho^{-1/3}$. Quantum mechanics provides us with a second natural length scale, the deBroglie wavelength, λ_{dB}, which is inversely proportional to the average momentum of the gas particles. For particles of mass m at a temperature T, we define $\lambda_{dB} = h/(2\pi m k_B T)^{1/2}$, where h and k_B are respectively Planck's and Boltzmann's constants. This particular definition comes from counting, by elementary statistical mechanics, the number of thermally accessible quantum states of a system (the "partition function"). It turns out that, for a gas of ideal, distinguishable particles, the average number of atoms per quantum state is $(\lambda_{dB}/d)^3$. The air we breathe has $d \sim 3$ nm and $\lambda_{dB} \sim 0.02$ nm, so that quantum states have an average population of $\sim 3 \times 10^{-7}$ atoms. Under such conditions, it is hardly necessary to consider what happens if more than one atom were to occupy a given quantum state. However, when the classical and quantum length scales become comparable, i.e. $\lambda_{dB}/d \sim 1$, then a quantum state has a significant probability of being occupied by more than one atom, and the statistics of identical particles must be taken into account. In this case, a gas of bosons experiences the "condensation" phenomenon identified by Einstein: a macroscopic fraction of the gas atoms are condensed into the single lowest quantum state.

How does this happen? It is analogous to laser action in an optical medium, where *stimulated emission* increases the probability of a photon being emitted into a mode of the radiation field, in proportion to the number of photons already present in that mode. The same principle governs the scattering of (boson) material particles: when two particles collide, the probability that either of them will scatter into a given quantum state is proportional to the existing state occupancy. When the average occupancy is less than a part per million, there is little prospect that any quantum state will accrete most of the particles of the gas. But if one state accumulates just a few particles, as happens in the early stages of Bose–Einstein condensation, then *stimulated scattering* ensures its eventual dominance.

The laser mechanism in optical and matter waves

A simplified model of an optical laser contains three main components: first, a resonant cavity, which targets a few modes of the radiation field for amplification; second, a gain medium, which feeds the target modes with additional photons; and third, an output coupler, which allows part of the built-up field in the cavity to be sent into the external world. Each of these components has a close relative in today's atom laser propotypes.

Instead of the quantized electromagnetic field, we deal with the quantized matter-wave field. In the analagous mathematical description, the creation and annihilation operators create or destroy a condensate atom. This picture caused some confusion in early discussions of the atom laser, for it is absurd to think that a whole sodium atom can be created out of the vacuum, or simply vanish without a trace. But its interpretation is straightforward: condensate atoms are created by transferring a thermal atom into the condensate, just as photons in a laser are created by the release of electromagnetic energy that is stored in the atoms (or molecules, etc.) of the gain medium. The resonant modes of the matter-wave field are represented by the condensate wavefunction Ψ (also called the order parameter), which is common to all condensate atoms. The cavity consists of an atom trap, which confines the condensate wave function, and thus provides a natural structure of normal modes.

The gain medium consists of the noncondensed portion of the atomic gas. This can be viewed, simplistically, as a classical thermal cloud of atoms that surrounds the condensate. When two atoms within this cloud collide, there is a preference for one of them to be scattered into the condensate, due to the mechanism of stimulated scattering of bosons analogous to the process of stimulated emission of photons. The kinetic theory of the generation of the condensate from the thermal cloud, near the temperature of the Bose–Einstein condensation phase transition, is an involved matter that is still being worked out,[4] but the equilibrium state of the system is well understood.[5]

Finally, we come to the ouput coupler. For an optical laser, this is usually a partially transmitting mirror. For an atom laser, it is an active subject of current research. Several output coupler schemes have been demonstrated. The simplest of these involve a change of internal state of the atom, by means of a radio-frequency or optical Raman transition, which converts the trap potential from confining to expelling. Atoms in a magnetic trap are confined by the alignment of their magnetic moments parallel to the field, so that they are reflected by the stronger magnetic field at the periphery of the trap. If their moments are reversed by a spin-flip transition, they will be accelerated into the strong-field region (or if their moments are rotated perpendicular to the field, they can fly ballistically out of the trap). Another form of output coupler uses light scattering to transfer controlled amounts of momentum to condensate atoms. This is most easily done by releasing the trap, and then promoting the atoms to a high momentum state by light scattering.

It should be noted that there is a significant qualitative difference between the performance of today's atom lasers and their optical counterparts: the attainable intensity of the beam. Atom laser action is produced by applying an ouput coupler to a stored mode that rarely contains more than 10^7 atoms, whereas even a millijoule pulse of an optical laser contains some 10^{15} photons. The relatively small number of atoms contained in present condensates reflects a fundamental limit, though this limit governs the maximum density of atoms, rather than their absolute numbers. Bose–Einstein condensation is essentially a dilute-gas phenomenon: collisions between condensate atoms generate correlations, which diminish the coherence of the condensate. Furthermore, all gaseous condensates produced to date are made up of highly reactive atoms—hydrogen, the alkalis, and metastable helium—and molecular recombination ensues when these gases reach a sufficient density. The highest attainable densities of condensates are now about 10^{14} – 10^{15} atoms/cm^3. There are prospects for increasing peak densities by control of atomic interactions, and of raising the absolute number of condensate atoms by using larger traps. But it will be challenging to raise the particle flux in outcoupled atomic beams to anything approaching that of the optical laser.

Figure 1 shows photographs of beams of atoms outcoupled from condensates produced in various laboratories since 1997. These are all photographic images of beams dispersed in space, with false color used to indicate the atom density. Both pulsed and quasi-continuous wave modes of operation are shown.

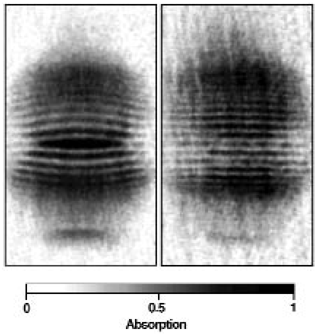


Figure 2. Interference fringes observed in the collisions of two initially separated Bose–Einstein condensates, which are released from a trap and collide as they fall. Left and right frames correspond to two different initial separations. From Ref. 10.

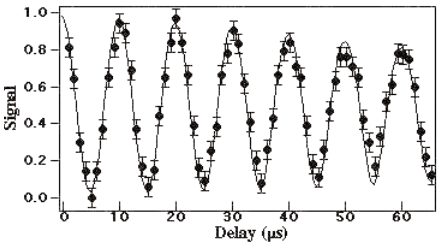


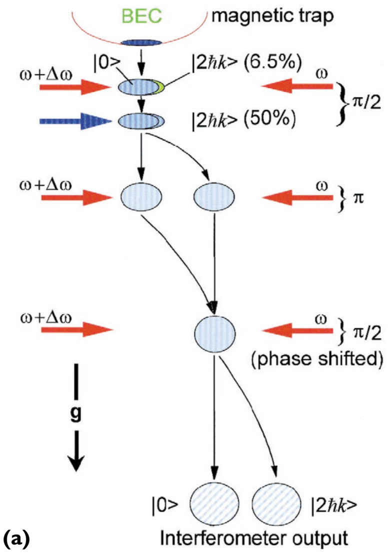
Figure 3. Interferometric measurement of the coherence of a Bose–Einstein condensate. Two optical standing-wave pulses, separated by a variable time delay, are applied to a condensate released from a trap. Each standing wave makes small copies of the condensate displaced in momentum space. The quantum mechanical amplitudes of each copy interfere, depending upon the delay between pulses and the spatial variation of the phase of the condensate wave function across its expanding profile. The experimental interferogram (points) exhibits good agreement with a theoretical calculation (solid line), which assumes a purely coherent condensate wave function.

Experiments with atom lasers

Having outlined, with many simplifications, the basic operation of today's atom lasers, we now review some of their first experimental results, focusing on those that illustrate key parallels with the optical regime. The first of these, the demonstration of matter-wave interference, shows the high degree of coherence that can be attained with atom laser sources. The laser analogy is appropriate here, because the visibility of these interference fringes in single-shot experiments requires a large number of atoms in the same mode. Up to the present, only Bose–Einstein condensates have provided the high mode occupancy ("degeneracy") required for such observations. The combination of matter-wave phase coherence and high degeneracy has also made it possible to demonstrate the phase-coherent amplification of matter waves, and the matter-wave analogue of optical four-wave mixing.

Matter-wave interference

A striking demonstration of the first-order coherence of matter waves, produced by Wolfgang Ketterle's group at MIT,[10] is shown in Fig. 2. In this experiment, two condensates of ^{23}Na atoms were prepared



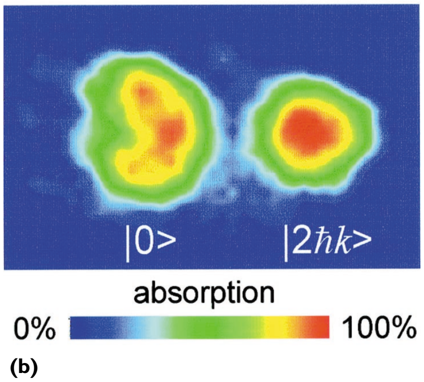


Figure 4. (a) Schematic of interferometric measurement of phase-coherent matter-wave amplification. The Bose–Einstein condensate (BEC) is released from the trap, and falls under gravity g, with the time sequence of events as illustrated. A small matter-wave seed pulse (6.5% of the atoms in the condensate) with two units of photon momentum is created by an optical standing wave. The seed is then amplified to contain 50% of the condensate atoms by use of an optical superradiance pulse. Imposition of a π pulse then causes the two separated clouds to recombine, and they are made to interfere by a subsequent π/2 pulse. (b) Absorption image of the two clouds prior to the π pulse, to illustrate their spatial separation. From Ref. 13.

in separate regions of a trap. The trap was then released, causing the two condensates to fall freely under the influence of gravity. When the expanding clouds came to overlap each other, a photograph was taken of the atomic density in a plane perpendicular to the direction of descent. The distinctive image of matter-wave interference that results is comparable to illustrations of the interference of monochromatic light that can be found in optics textbooks.

Figure 3 provides another illustration of the degree of coherence of the matter wave function attainable in these systems, as seen by the Laser Cooling and Trapping Group at the National Institute of Standards and Technology (NIST), in Gaithersburg, MD.[11] In this experiment, a ^{23}Na condensate was released from a trap and exposed to two standing-wave light pulses separated by a time delay. Each pulse produces a small "copy" of the initial condensate wave function, with a boost of two units of photon momentum. These two copies travel away from the condensate at the same velocity, maintaining a constant spatial overlap determined by the delay between light pulses. When well separated from the condensate, the output wave is photographed, demonstrating matter-wave interference of the two copies (Fig. 3). Quantitative intepretation of the interference signal is aided by comparison with a theoretical calculation, also shown in Fig. 3, which is based on solution of the time-dependent Gross–Pitaevski equation[5] that describes the evolution of a pure Bose–Einstein condensate. The good agreement between experiment and theory[11] indicates that the initial condensate wave function has a spatially uniform phase.

Phase-coherent amplification of matter waves

The experiments described above illustrate the first-order coherence properties of atomic beams emerging from a condensate, but sharp contrast of interference fringes does not constitute direct evidence for the existence of laser-type action. Such fringes could be produced by a sufficiently monochromatic (i.e., monoenergetic) classical atomic beam, just as high-contrast interference fringes can be produced by filtered classical light. Indeed, one of the most striking demonstrations of matter-wave interference yet produced, a synthetic atomic hologram, used a cooled, non-condensed atomic source.[12] However, late in 1999, two groups demonstrated phase-coherent amplification of matter waves by Bose–Einstein condensates, a process closely analogous to amplification of a coherent optical wave in an optical laser amplifier. We discuss this with reference to the experiment reported by Mikio Kozuma *et al.*;[13] the MIT experiment[14] is similar.

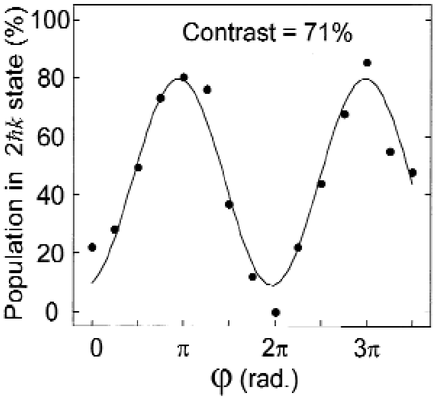


Figure 5. Mach–Zehnder interferogram from the setup depicted in Fig. 4. The population in the momentum-boosted state is plotted as a function of the phase shift of the final π/2 pulse. From Ref. 13.

A schematic of the matter-wave amplification scheme is shown in Fig. 4. A condensate of ^{87}Rb atoms is released from a trap and irradiated by a standing light wave which, as in the NIST experiment described above, imparts two units of photon momentum to a small fraction of the condensate atoms (6.5% in the example described here). This constitutes a seed pulse, which would ordinarily simply fly out of the condensate. But in this experiment, a gain medium is created by imposition of a "superradiance" light pulse on the condensate. Such a pulse would ordinarily scatter condensate atoms randomly into different momentum states, and this is seen if no seed pulse is present. However, the seed pulse constitutes a populated matter-wave mode; condensate atoms will thus tend to scatter light so that they can join that mode, and so the seed pulse population is amplified. Amplification factors in excess of 10 were attained in this experiment.

The phase coherence of the amplification process is demonstrated by interfering the amplified wave with the original condensate. As shown in Fig. 3, after the condensate and the amplified wave are separated in space, their momenta are switched by an optical π pulse, and they subsequently come back together. When they overlap, a π/2 pulse recombines these two waves coherently, yielding the interference pattern shown in Fig. 5. The phase of the final π/2 optical pulse is referenced to that of the light that created the initial matter-wave seed pulse. Thus the phase of the amplified matter wave is locked to that of the seed pulse.

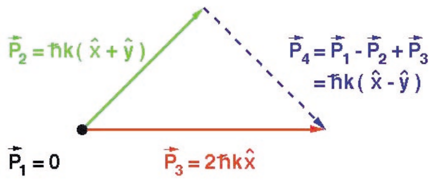


Figure 6. Geometry of four-wave mixing experiment. $\mathbf{p}_2$ and $\mathbf{p}_3$ are atomic momenta acquired from optical standing waves. From Ref.

Four-wave mixing of matter waves

Today's atom laser systems differ in one essential way from their simplest optical counterparts: due to the strength of atomic interactions, the matter-wave medium has a strong third-order nonlinearity. It may be possible to eliminate this strong third-order nonlinearity by artificially reducing the atomic interactions, but this has not yet been achieved in practice. We now show how the nonlinearity of the medium has made it possible to realize the matter-wave analogue of optical four-wave mixing.

The time evolution of the condensate wavefunction Ψ is described by the Gross–Pitaevski (or nonlinear Schrödinger) equation, which contains a potential proportional to $|\Psi|^2$ that derives from atomic interactions. This is analogous to Maxwell's equations for the propagation of light in a medium whose polarizability depends linearly upon light intensity, which gives rise to sum-frequency generation. Thus similar phenomena can be found in matter waves. The one that has received the greatest attention to date is four-wave mixing.

The Gross–Pitaevski equation for $d\Psi/dt$ contains a term proportional to $\Psi^* \Psi^2$. Thus if Ψ initially has momentum components $\mathbf{p}_1$, $\mathbf{p}_2$, and $\mathbf{p}_3$, then a component $\mathbf{p}_4 = \mathbf{p}_1 - \mathbf{p}_2 + \mathbf{p}_3$ will be created. This has been demonstrated in an experiment at NIST.[15] Once again, optical manipulation of atomic beams plays a critical role. A ^{23}Na condensate at rest provides the momentum component $\mathbf{p}_1 = 0$. Sequential illumination of the condensate by two standing light waves at 45° orientation provides the components $\mathbf{p}_2$ and $\mathbf{p}_3$, from which $\mathbf{p}_4$ should be generated, as shown schematically in Fig. 6. The conservation of momentum in this scheme is equivalent to phase matching in optical four-wave mixing. Applying the two light waves to the condensate ($\mathbf{p}_1$) generates the components $\mathbf{p}_2$ and $\mathbf{p}_3$, and the component $\mathbf{p}_4$ is seen to emerge (Fig. 7).

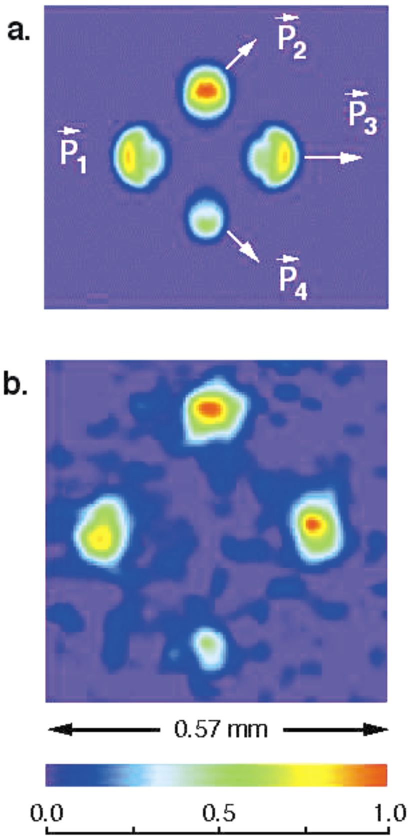


Figure 7. Generation of fourth momentum component in the four-wave mixing experiment of Ref. 15. False color displays densities of condensate components, which have flown apart due to their separate momenta. (a) simulation by solution of a two-dimensional Gross–Pitaevski equation. (b) experimental data.

We emphasize that just as optical four-wave mixing requires high-intensity coherent light sources to build up the generated wave, a Bose–Einstein condensate is necessary for the coherent generation of matter waves in this scheme. If our gas were above the condensation transition temperature, the number density would be reduced and the phase matching condition would be different for each velocity class. Both factors would greatly diminish the conversion efficiency.

Conclusion

The techniques of laser cooling and trapping have made it possible to generate atomic beams that have the spectral purity, intensity, and coherence properties characteristic of early laser sources of light, and can bring us into the regime of nonlinear atom optics. Although rapid progress has been made in this field during the past five years, we still are only beginning to explore its potential. For example, atoms, unlike photons, are available in both bosonic and fermionic varieties, and during the past two years there have been demonstrations of the effects of quantum statistics in laser-cooled fermion gases,[16] and in boson-fermion mixtures.[17] Soliton motions, akin to those encountered in propagation in optical fibers, have been observed,[18-20] as have vortex motions in rotating condensates.[21-23] In all these matter-wave studies, optics, one of the most ancient and one of the most modern of sciences, serves as an indispensable practical tool and a continuous source of inspiration.

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