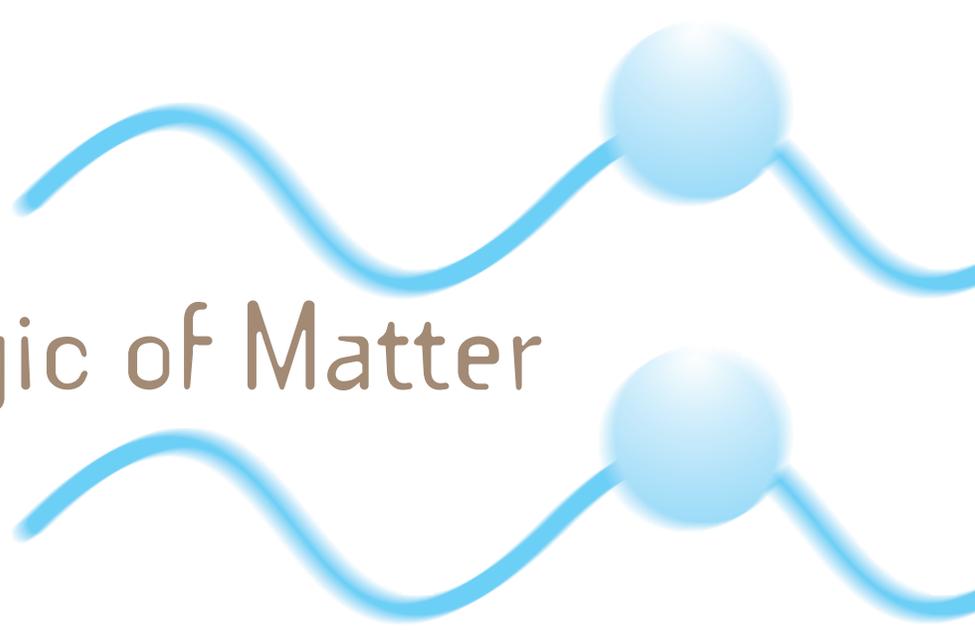


Wolfgang Ketterle

The Magic of Matter Waves



The hypothesis of Louis de Broglie in 1924 that all material particles have wave properties is one of the basic tenets of quantum physics. The duality that particles propagate as waves, but are detected as particles, is one of the counterintuitive aspects of physics that every student has to digest. However, the wavelength of the de Broglie waves is so small that the wave character of matter only becomes manifest in the microscopic domain. For example, the matter wavelength of room temperature atoms is smaller than the atom itself. The wavelength of a macroscopic body is more than a billion times smaller. This is the reason we don't experience the wave properties of matter in everyday life.

This situation dramatically changes at extremely low temperatures when the motion of particles slows down and their de Broglie wavelength λ_{db} , which is inversely

proportional to their velocity v , increases: $\lambda_{db} = h/mv$. Here h is Planck's constant and m the atomic mass. Recent advances in atom cooling makes it now possible to reach nanokelvin temperatures. The matter wavelength of atoms, which is of subatomic scale at room temperature, becomes macroscopic at such low temperatures and determines the properties of a gaseous sample, the size of which is comparable to the thickness of a hair. Atomic matter waves can now be directly photographed, and ultracold matter with novel properties can be studied.

The wavelike properties of atoms become very dramatic through the phenomenon of Bose-Einstein condensation (BEC). When the temperature is sufficiently low and the de Broglie wavelength of the atoms becomes comparable to the distance between atoms, then almost all the atoms occupy a single quantum state. They become one giant matter wave all oscillating in phase. This new form of

matter is called a Bose-Einstein condensate. The 1997 issue of *physics@mit* included a description of this phenomenon and of the experimental verification of the coherence of the condensate done in Prof. Ketterle's group. That article also described the cooling and trapping techniques necessary to produce condensates. Many of these techniques were pioneered by groups at MIT led by Professors Pritchard, Greytak and Kleppner.

After the feat of cooling an initially hot gas down to nanokelvin temperatures is accomplished, one obtains a cloud of about ten million sodium atoms in a volume of a fraction of a millimeter, at a density one hundred thousand times less than air. This cloud is magnetically suspended and confined in an ultrahigh vacuum chamber. The study of its properties is currently one of the hottest areas in physics and the topic of about 500 scientific publications every year.

Research on gaseous BEC can be divided into two areas: In the first (which could be labeled "The atomic condensate as a coherent gas", or "Atom lasers"), one would like to have as little interaction as possible - almost like the photons in a laser. The experiments are preferentially done at low densities. The Bose-Einstein condensate serves as an intense source of ultracold coherent atoms for experiments in atom optics, in precision studies or for explorations of basic aspects of quantum mechanics. The second area could be labeled as "BEC as a new quantum fluid" or "BEC as a many-body system". The focus here is on the interactions between

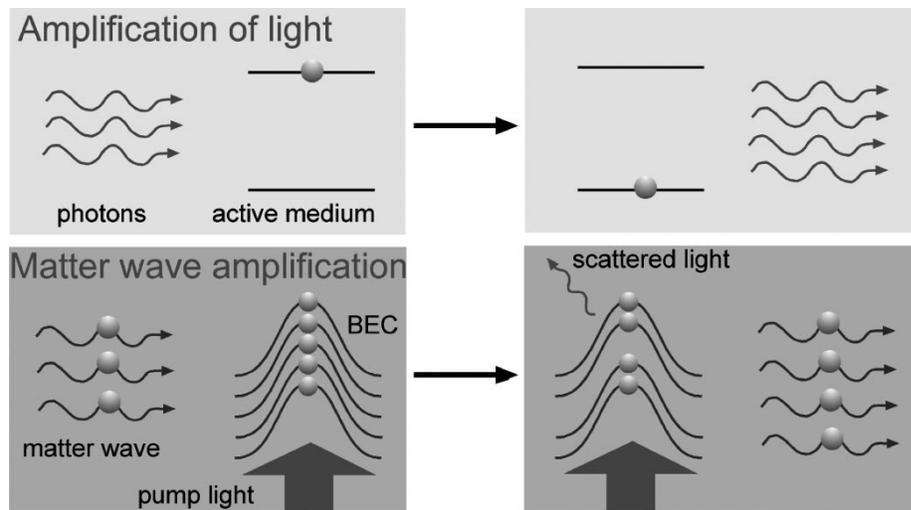


FIGURE 1
Amplification of light and atoms:
 In the optical laser, light is amplified by passing it through an excited inverted medium. In the MIT atom amplifier, an input matter wave is sent through a Bose-Einstein condensate illuminated by laser light. Bosonic stimulation by the input atoms causes light to be scattered by the condensate exactly at the angle at which a recoiling condensate atoms joins the input matter wave and augments it.

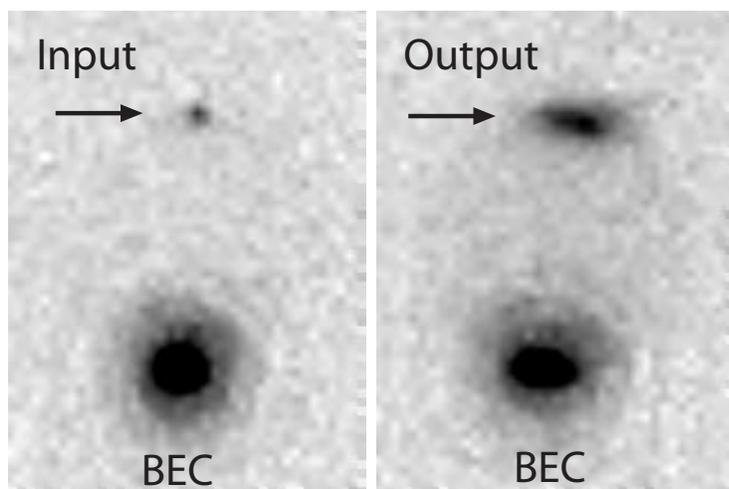


FIGURE 2

Observation of atom amplification.

Atom amplification is probed by sending an input beam through the atom amplifier, which is a Bose-Einstein condensate (BEC) illuminated with laser light. On the left side, the input beam has passed through the condensate without amplification. 20 ms later, a shadow picture is taken of the condensate and the input atoms. When the amplification process is activated by illuminating the condensate with laser light, the output pulse contains many more atoms than the input pulse – typical amplification factors are between 10 and 100. The field of view is 1.9 mm x 2.6 mm.

the atoms which are most pronounced at high densities. In this article, both areas are illustrated with recent results of Ketterle’s group. The coherent amplification of atoms is an example of atom optics with BEC, and the study of vortices addresses the superfluid properties of the gas.

Amplification of atoms in a Bose-Einstein condensate

Since atoms are de Broglie waves, there are many analogies between atoms and light that consists of electromagnetic waves. This is exploited in the field of atom optics where

atoms are reflected, diffracted and interfere using various atom-optical elements. The field of atom optics was pioneered by Professor Dave Pritchard in the 1980s.

One important question was whether these analogies could be extended to the optical laser that is based on the amplification of light. When Ketterle’s research team developed the atom laser in 1997, the atomic amplification process happened during the formation of the Bose-Einstein condensate. Since then, people have questioned whether atoms can be amplified the way light passing through an optical laser is amplified. In 1999, Ketterle’s group in collaboration with Pritchard’s group found a way to do just that.

Amplifying atoms is more subtle than amplifying the electromagnetic waves that make up radio waves or light, because atoms can only change their quantum state and cannot be created or destroyed. Therefore, even if one could amplify gold atoms, one would not realize the dreams of medieval alchemy. An atom amplifier converts atoms from the active medium into an atomic wave that is exactly in the same quantum state as the input wave (*Figure 1*).

The atom amplifier requires a reservoir, or an active medium, of ultracold atoms that have a very narrow spread of velocities and can be transferred to the atomic beam. A natural choice for the reservoir is a Bose-Einstein condensate where the atoms form a single “giant” matter wave and don’t move randomly any more. One also needs a coupling mechanism that transfers atoms from the reservoir at rest to an input mode while conserving energy and momentum. This transfer of atoms is accomplished by scattering laser light. The recoil of the scattering process accelerates some atoms to exactly match the velocity of the input atoms. Not only are the atoms amplified, but they are in exactly the same motional state as the input atoms; *i.e.*, they have the same quantum-mechanical phase. This is verified by interfering the amplified output with a copy of the input wave and observing phase coherence.

This direct observation of atom amplification was preceded by a surprising occurrence late one night in October 1998. The researchers happened to illuminate a

BEC with laser light from a specific direction and of a specific polarization. It emitted highly directional beams of atoms and light. Several months later, they realized that this phenomenon, which they called a new form of superradiance, was actually a new mechanism for matter wave amplification.

The demonstration of an atom amplifier adds a new element to atom optics. In addition to passive elements like beam splitters, lenses and mirrors, there is now an active atom-optical element. Coherent matter wave amplifiers may improve the performance of atom interferometers by making up for losses inside the device or by amplifying the output signal. Atom interferometers are the matter-wave analogues of optical interferometers, highly precise sensors using the interference of two laser beams, and are already used as precise gravity and rotation sensors.

Collaborators with Professors Ketterle and Pritchard were MIT physics graduate students Shin Inouye, Subhadeep Gupta, Ananth P. Chikkatur, postdoctoral fellow Axel Görlitz and visiting scientist Prof. Tilman Pfau from the University of Stuttgart in Germany.

Observation of Vortex Lattices in Bose-Einstein Condensates

Quantum mechanics and the wave nature of matter have subtle manifestations when particles have angular momentum, or more generally, when quantum systems are rotating.

When a quantum-mechanical particle moves in a circle the circumference of the orbit has to be an integer multiple of the de Broglie wavelength. This “quantization rule” leads to the Bohr model and the discrete energy levels of the hydrogen atom. For a rotating superfluid, it leads to quantized vortices.

If one spins a normal liquid in a bucket, the fluid will rotate, after an initial transient, as a rigid body where the velocity smoothly increases from the center to the edge (*Figure 3, left*). However, this smooth variation is impossible for particles in a single quantum state. To fulfill the above-mentioned quantization rule, the flow field has to develop singular regions where the number of de Broglie wavelengths on a closed path jumps up by one. Energetically, the most favorable configuration for this is an array of vortices, which are whirlpools similar to tornados or the flow of water in a flushing toilet. However, the whirlpools in a Bose-Einstein condensate are quantized – when an atom goes around the vortex core, its quantum mechanical phase changes by exactly 2π .

Such quantized vortices play a key role in superfluidity and superconductiv-

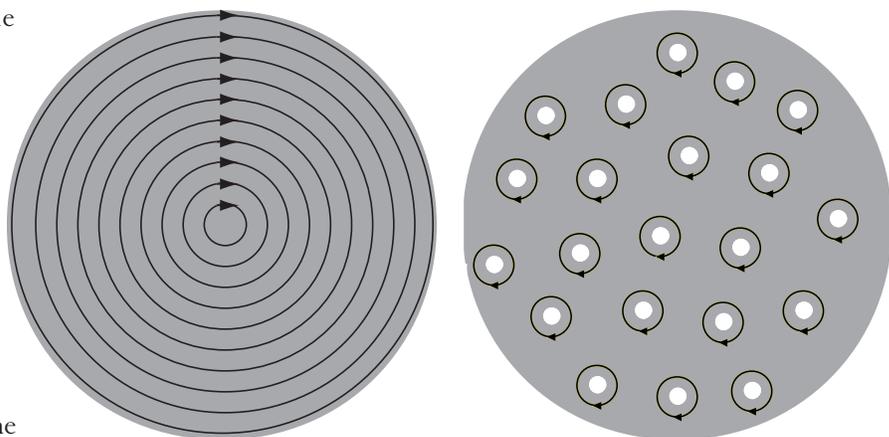


FIGURE 3
Comparison of the flow fields of rotating normal liquids and superfluids. A normal fluid (left) undergoes rigid body rotation, whereas a superfluid develops an array of quantized vortices.

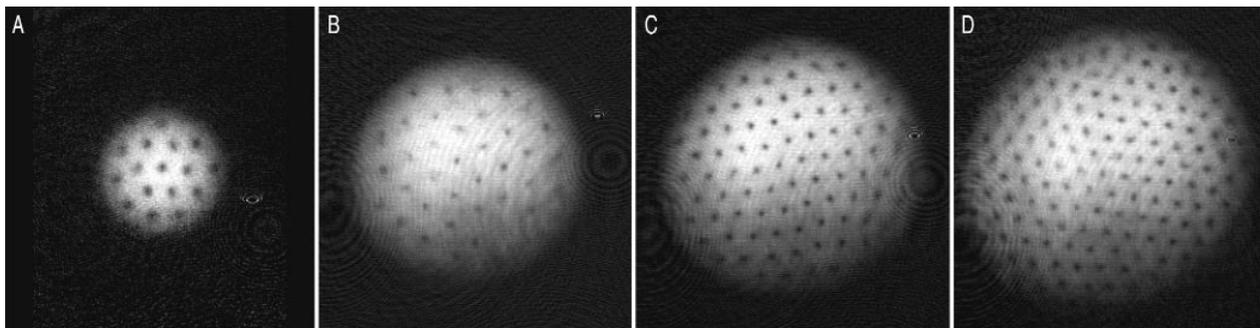


FIGURE 4

Observation of vortex lattices.

The examples shown contain (A) 16 (B) 32 (C) 80 and (D) 130 vortices as the speed of rotation is increased. The vortices have “crystallized” in a triangular pattern. The diameter of the cloud in (D) is 1 mm after ballistic expansion, which represents a magnification of 20.

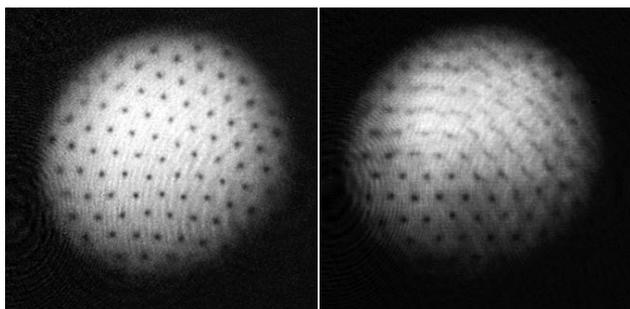


FIGURE 5

Vortex lattices with defects. In the left image, the lattice has a dislocation near the center of the condensate. In the right one, there is a defect reminiscent of a grain boundary.

ity. In superconductors, magnetic flux lines arrange themselves in regular lattices that have been directly imaged. In superfluids, direct observation of vortices had been limited to small arrays (up to 11 vortices), both in liquid ^4He and in rotating gaseous Bose-Einstein condensates (BEC) by a group in Paris. Ketterle’s group has recently observed the formation of highly-ordered vortex lattices in a rotating Bose-condensed gas. They are produced by stirring the condensate with a laser beam, thus setting it into rotation. The condensate, which is a gas cloud 100,000 thinner than air, then exhibits a remarkable manifestation of quantum mechanics at a macro-

scopic level. The rotating gas cloud is riddled with more than 100 vortices. Since the vortex cores are smaller than the optical resolution, the gas is allowed to ballistically expand after the magnetic trap is switched off. This magnifies the spatial structures twenty fold. A shadow picture of these clouds shows little bright spots where the light penetrates through the empty vortex cores (*Figure 4* shows a negative image).

A striking feature of the observed vortex lattices is the extreme regularity, free of any major distortions, even near the boundary. Such “Abrikosov” lattices

were first predicted for quantized magnetic flux lines in type-II superconductors. However, nature is not always perfect: Some of the images show distortions or defects of the vortex lattices. Two examples are shown in *Figure 5*.

The observation of vortices in gaseous Bose-Einstein condensate is the starting point for many further studies. How are vortices formed? How do they decay? Are the vortices straight or bent? Such experiments can be directly compared with first principles calculations that are possible for such a dilute system. This interplay between theory and experiment may lead to a better understanding of superfluidity and macroscopic quantum phenomena.

Prof. Ketterle’s collaborators on the vortex project are MIT physics graduate students Jamil Abo-Shaeer, Kaiwen Xu and postdoctoral associates Chandra Raman and Johnny Vogels.

Outlook

The rapid pace of developments in atomic BEC during the last few years has taken the community by surprise. After decades of an elusive search, nobody expected that condensates would be so robust and relatively easy to manipulate. Also, nobody imagined that such a simple system would pose so many challenges, not only to experimentalists, but also to our fundamental understanding of physics. The list of future challenges is long and includes the exploration of superfluidity and second sound in Bose gases, the study of quantum-degenerate molecules and Fermi gases, the development of practical “high-power” atom lasers, and their application in atom optics and precision measurements.

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WOLFGANG KETTERLE is the John D. MacArthur Professor of Physics at MIT. His group is working on novel methods to cool, trap and manipulate atoms with the goal of exploring novel aspects of ultracold atomic matter. He co-invented the Dark SPOT trap and combined laser cooling and evaporative cooling, which became key techniques to obtain Bose-Einstein condensation in dilute atomic gases. He was among the very first scientists to observe this phenomenon in 1995, and realized the first atom laser in 1997. His awards include a David and Lucile Packard Fellowship (1996), the Rabi Prize of the American Physical Society (1997), the Gustav-Hertz Prize of the German physical society (1997), the Discover Magazine Award for Technological Innovation (1998), the Fritz London Prize in Low Temperature Physics (1999), the Dannie-Heineman Prize of the Academy of Sciences, Göttingen, Germany (1999), and the Benjamin Franklin Medal in Physics (2000).