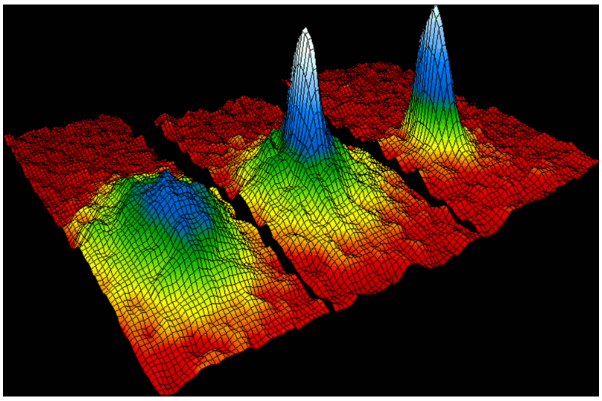
Bose–Einstein condensate



Velocity-distribution data of a gas of rubidium atoms, confirming the discovery of a new phase of matter, the Bose–Einstein condensate.

A **Bose–Einstein condensate** **(BEC)** is a state of matter of a dilute gas of weakly interacting bosons confined in an external potential and cooled to temperatures very near to absolute zero (0 K, −273.15 °C, or −459.67 °F). Under such conditions, a large fraction of the bosons collapse into the lowest quantum state of the external potential, and all wave functions overlap each other, at which point quantum effects become apparent on a macroscopic scale.

This state of matter was first predicted by Satyendra Nath Bose and Albert Einstein in 1924–25. Bose first sent a paper to Einstein on the quantum statistics of light quanta (now called photons). Einstein was impressed, translated the paper himself from English to German and submitted it for Bose to the *Zeitschrift für Physik* which published it. Einstein then extended Bose's ideas to material particles (or matter) in two other papers.[1]

Seventy years later, the first gaseous condensate was produced by Eric Cornell and Carl Wieman in 1995 at the University of Colorado at Boulder NIST-JILA lab, using a gas of rubidium atoms cooled to 170 nanokelvin (nK) [2] (1.7 K). Cornell, Wieman, and Wolfgang Ketterle at MIT were awarded the 2001 Nobel Prize in Physics in Stockholm, Sweden for their achievements.[3]

Introduction

"Condensates" are extremely low-temperature fluids which contain properties and exhibit behaviors that are currently not completely understood, such as spontaneously flowing out of their containers. The effect is the consequence of quantum mechanics, which states that since continuous spectral regions can typically be neglected, systems can almost always acquire energy only in discrete steps. If a system is at such a low temperature that it is in the lowest energy state, it is no longer possible for it to reduce its energy, not even by friction. Without friction, the fluid will easily overcome gravity because of adhesion between the fluid and the container wall, and it will take up the most favorable position (all around the container).[4]

Bose–Einstein condensation is an exotic quantum phenomenon that was observed in dilute atomic gases for the first time in 1995, and is now the subject of intense theoretical and experimental study.[5]

Theory

The slowing of atoms by use of cooling apparatuses produces a singular quantum state known as a **Bose condensate** or **Bose–Einstein condensate**. This phenomenon was predicted in 1925 by generalizing Satyendra Nath Bose's work on the statistical mechanics of (massless) photons to (massive) atoms. (The Einstein manuscript, once believed to be lost, was found in a library at Leiden University in 2005.[6]) The result of the efforts of Bose and Einstein is the concept of a Bose gas, governed by Bose–Einstein statistics, which describes the statistical distribution of identical particles with integer spin, now known as bosons. Bosonic particles, which include the photon as well as atoms such as helium-4, are allowed to share quantum states with each other. Einstein demonstrated that cooling bosonic atoms to a very low temperature would cause them to fall (or "condense") into the lowest accessible quantum state, resulting in a new form of matter.

This transition occurs below a critical temperature, which for a uniform three-dimensional gas consisting of non-interacting particles with no apparent internal degrees of freedom is given by:

$$T_c = \left(\frac{n}{\zeta(3/2)}\right)^{2/3} \frac{2\pi\hbar^2}{mk_B}$$

where:

T_c	is	the critical temperature,
n	is	the particle density,
m	is	the mass per boson,
$\hbar$	is	the reduced Planck constant,
k_B	is	the Boltzmann constant, and
ζ	is	the Riemann zeta function; $\zeta(3/2) \approx 2.6124.$ (sequence A078434 [7] in OEIS)

Einstein's Argument

Consider a collection of N noninteracting particles which can each be in one of two quantum states, $|0\rangle$ and $|1\rangle$. If the two states are equal in energy, each different configuration is equally likely.

If we can tell which particle is which, there are 2^N different configurations, since each particle can be in $|0\rangle$ or $|1\rangle$ independently. In almost all the configurations, about half the particles are in $|0\rangle$ and the other half in $|1\rangle$. The balance is a statistical effect, the number of configurations is largest when the particles are divided equally.
If the particles are indistinguishable, however, there are only N+1 different configurations. If there are K particles in state $|0\rangle$, there are N-K particles in state $|1\rangle$. Whether any particular particle is in state $|0\rangle$ or in state $|1\rangle$ cannot be determined, so each value of K determines a unique quantum state for the whole system. If all these states are equally likely, there is no statistical spreading out; it is just as likely for all the particles to sit in $|0\rangle$ as for the particles to be split half and half.

Suppose now that the energy of state $|1\rangle$ is slightly greater than the energy of state $|0\rangle$ by an amount E. At temperature T, a particle will have a lesser probability to be in state $|1\rangle$ by exp(-E/T). In the distinguishable case, the particle distribution will be biased slightly towards state $|0\rangle$ and the distribution will be slightly different from half and half. But in the indistinguishable case, since there is no statistical pressure toward equal numbers, the most likely outcome is that most of the particles will collapse into state $|0\rangle$.

In the distinguishable case, for large N, the fraction in state $|0\rangle$ can be computed. It is the same as coin flipping with a coin which has probability p = exp(-E/T) to land tails. The fraction of heads is 1/(1+p), which is a smooth function of p, of the energy.
In the indistinguishable case, each value of K is a single state, which has its own separate Boltzmann probability. So the probability distribution is exponential:

$$P(K) = Ce^{-KE/T} = Cp^K.$$

For large N, the normalization constant C is (1-p). The expected total number of particles which are not in the lowest energy state, in the limit that $N \to \infty$, is equal to $\sum_{n>0} Cnp^n = p/(1-p)$. It doesn't grow when N is large, it just approaches a constant. This will be a negligible fraction of the total number of particles. So a collection of enough bose particles in thermal equilibrium will mostly be in the ground state, with only a few in any excited state, no matter how small the energy difference.

Consider now a gas of particles, which can be in different momentum states labelled $|k\rangle$. If the number of particles is less than the number of thermally accessible states, for high temperatures and low densities, the particles will all be in different states. In this limit the gas is classical. As the density increases or the temperature decreases, the number of accessible states per particle becomes smaller, and at some point more particles will be forced into a single state than the maximum allowed for that state by statistical weighting. From this point on, any extra particle added will go into the ground state.

To calculate the transition temperature at any density, integrate over all momentum states the expression for maximum number of excited particles p/(1-p):

$$N = V \int \frac{d^3k}{(2\pi)^3} \frac{p(k)}{1 - p(k)} = V \int \frac{d^3k}{(2\pi)^3} \frac{1}{e^{\frac{k^2}{2mT}} - 1}$$

$$p(k) = e^{\frac{-k^2}{2mT}}.$$

When the integral is evaluated with the factors of k_B and $\hbar$ restored by dimensional analysis, it gives the critical temperature formula of the preceding section. Therefore, this integral defines the critical temperature and particle number corresponding to the conditions of zero chemical potential (μ = 0 in the Bose–Einstein statistics distribution).

The Gross–Pitaevskii equation

The state of the BEC can be described by the wavefunction of the condensate $\psi(\vec{r})$. For a system of this nature, $|\psi(\vec{r})|^2$ is interpreted as the particle density, so the total number of atoms is $N = \int d\vec{r}|\psi(\vec{r})|^2$

Provided essentially all atoms are in the condensate (that is, have condensed to the ground state), and treating the bosons using mean field theory, the energy (E) associated with the state $\psi(\vec{r})$ is:

$$E = \int d\vec{r} \left[\frac{\hbar^2}{2m} |\nabla\psi(\vec{r})|^2 + V(\vec{r})|\psi(\vec{r})|^2 + \frac{1}{2} U_0 |\psi(\vec{r})|^4 \right]$$

Minimising this energy with respect to infinitesimal variations in $\psi(\vec{r})$, and holding the number of atoms constant, yields the Gross-Pitaevski equation (GPE) (also a non-linear Schrödinger equation):

$$i\hbar \frac{\partial \psi(\vec{r})}{\partial t} = \left(-\frac{\hbar^2 \nabla^2}{2m} + V(\vec{r}) + U_0 |\psi(\vec{r})|^2 \right) \psi(\vec{r})$$

where:

m	is the mass of the bosons,
$V(\vec{r})$	is the external potential,
U_0	is representative of the inter-particle interactions.

The GPE provides a good description of the behavior of BEC's and is thus often applied for theoretical analysis.

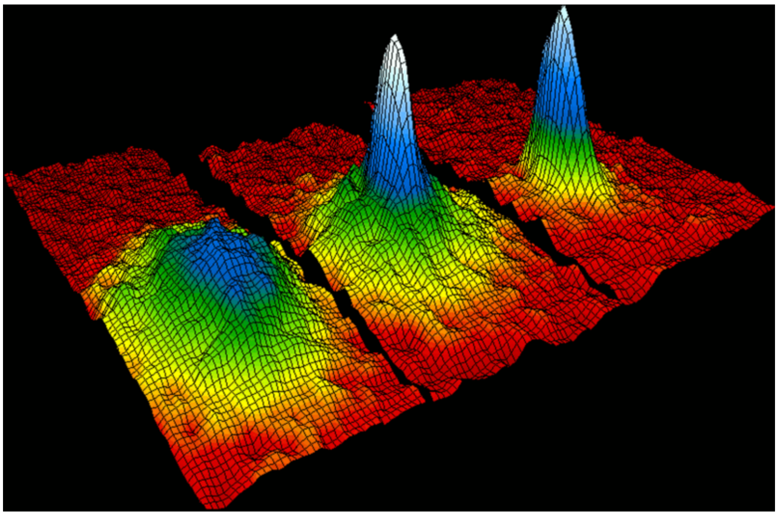
Discovery

In 1938, Pyotr Kapitsa, John Allen and Don Misener discovered that helium-4 became a new kind of fluid, now known as a superfluid, at temperatures less than 2.17 K (the lambda point). Superfluid helium has many unusual properties, including zero viscosity (the ability to flow without dissipating energy) and the existence of quantized vortices. It was quickly realized that the superfluidity was due to Bose–Einstein condensation of quasiparticles – the elementary excitations in the low-energy spectrum of liquid helium. In fact, many of the properties of superfluid helium also appear in the gaseous Bose–Einstein condensates created by Cornell, Wieman and Ketterle (see below). Superfluid helium-4 is a liquid rather than a gas, which means that the interactions between the atoms are relatively strong; the original theory of Bose–Einstein condensation must be heavily modified in order to describe it. Bose–Einstein condensation remains, however, fundamental to the superfluid properties of helium-4.

The first "pure" Bose–Einstein condensate was created by Eric Cornell, Carl Wieman, and co-workers at JILA on June 5, 1995. They did this by cooling a dilute vapor consisting of approximately two thousand rubidium-87 atoms to below 170 nK using a combination of laser cooling (a technique that won its inventors Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips the 1997 Nobel Prize in Physics) and magnetic evaporative cooling. About four months later, an independent effort led by Wolfgang Ketterle at MIT created a condensate made of sodium-23. Ketterle's condensate had about a hundred times more atoms, allowing him to obtain several important results such as the observation of quantum mechanical interference between two different condensates. Cornell, Wieman and Ketterle won the 2001 Nobel Prize in Physics for their achievement.[8]

The Bose–Einstein condensation also applies to quasiparticles in solids. A magnon in an antiferromagnet carries spin 1 and thus obeys Bose–Einstein statistics. The density of magnons is controlled by an external magnetic field, which plays the role of the magnon chemical potential. This technique provides access to a wide range of boson densities from the limit of a dilute Bose gas to that of a strongly interacting Bose liquid. A magnetic ordering observed at the point of condensation is the analog of superfluidity. In 1999 Bose condensation of magnons was demonstrated in the antiferromagnet $TlCuCl_3$.[9] The condensation was observed at temperatures as large as 14 K. Such a high transition temperature (relative to that of atomic gases) is due to the greater density achievable with magnons and the smaller mass (roughly equal to the mass of an electron). In 2006, condensation of magnons in ferromagnets was even shown at room temperature,[10] where the authors used pumping techniques.

Velocity-distribution data graph



Velocity-distribution data of a gas of rubidium atoms, confirming the discovery of a new phase of matter, the Bose–Einstein condensate. Left: just before the appearance of a Bose–Einstein condensate. Center: just after the appearance of the condensate. Right: after further evaporation, leaving a sample of nearly pure condensate.

In the image accompanying this article, the velocity-distribution data indicates the formation of a Bose–Einstein condensate out of a gas of rubidium atoms. The false colors indicate the number of atoms at each velocity, with red being the fewest and white being the most. The areas appearing white and light blue are at the lowest velocities. The peak is not infinitely narrow because of the Heisenberg uncertainty principle: since the atoms are trapped in a particular region of space, their velocity distribution necessarily possesses a certain minimum width. This width is given by the curvature of the magnetic trapping potential in the given direction. More tightly confined directions have bigger widths in the ballistic velocity distribution. This anisotropy of the peak on the right is a purely quantum-mechanical effect and does not exist in the thermal distribution on the left. This famous graph served as the cover-design for 1999 textbook *Thermal Physics* by Ralph Baierlein.[11]

Vortices

As in many other systems, vortices can exist in BECs. These can be created, for example, by 'stirring' the condensate with lasers, or rotating the confining trap. The vortex created will be a quantum vortex. These phenomena are allowed for by the non-linear $|\psi(\vec{r})|^2$ term in the GPE. As the vortices must have quantised angular momentum, the wavefunction will be of the form $\psi(\vec{r}) = \phi(\rho, z)e^{i\ell\theta}$ where ρ, z and θ are as in the cylindrical coordinate system, and ℓ is the angular number. To determine $\phi(\rho, z)$, the energy of $\psi(\vec{r})$ must be minimised, according to the constraint $\psi(\vec{r}) = \phi(\rho, z)e^{i\ell\theta}$. This is usually done computationally, however in a uniform medium the analytic form

$$\phi = \frac{nx}{\sqrt{2 + x^2}}$$

where:

n^2	is	density far from the vortex,
$x = \frac{\rho}{\ell\xi}$,		
ξ	is	healing length of the condensate.

demonstrates the correct behavior, and is a good approximation.

A singly-charged vortex ($\ell = 1$) is in the ground state, with its energy ϵ_v given by

$$\epsilon_v = \pi n \frac{\hbar^2}{m} \ln\left(1.464\frac{b}{\xi}\right)$$

where:

b	is	the farthest distance from the vortex considered.

(To obtain an energy which is well defined it is necessary to include this boundary b .)

For multiply-charged vortices ($\ell > 1$) the energy is approximated by

$$\epsilon_v \approx \ell^2 \pi n \frac{\hbar^2}{m} \ln\left(\frac{b}{\xi}\right)$$

which is greater than that of ℓ singly-charged vortices, indicating that these multiply-charged vortices are unstable to decay. Research has, however, indicated they are metastable states, so may have relatively long lifetimes.

Closely related to the creation of vortices in BECs is the generation of so-called dark solitons in one-dimensional BECs. These topological objects feature a phase gradient across their nodal plane, which stabilizes their shape even in propagation and interaction. Although solitons carry no charge and are thus prone to decay, relatively long-lived dark solitons have been produced and studied extensively.[12]

Unusual characteristics

Further experimentation by the JILA team in 2000 uncovered a hitherto unknown property of Bose–Einstein condensates. Cornell, Wieman, and their coworkers originally used rubidium-87, an isotope whose atoms naturally repel each other, making a more stable condensate. The JILA team instrumentation now had better control over the condensate so experimentation was made on naturally *attracting* atoms of another rubidium isotope, rubidium-85 (having negative atom-atom scattering length). Through a process called Feshbach resonance involving a sweep of the magnetic field causing spin flip collisions, the JILA researchers lowered the characteristic, discrete energies at which the rubidium atoms bond into molecules, making their Rb-85 atoms repulsive and creating a stable condensate. The reversible flip from attraction to repulsion stems from quantum interference among condensate atoms which behave as waves.

When the scientists raised the magnetic field strength still further, the condensate suddenly reverted back to attraction, imploded and shrank beyond detection, and then exploded, blowing off about two-thirds of its 10,000 or so atoms. About half of the atoms in the condensate seemed to have disappeared from the experiment altogether, not being seen either in the cold remnant or the expanding gas cloud.[13] Carl Wieman explained that under current atomic theory this characteristic of Bose–Einstein condensate could not be explained because the energy state of an atom near absolute zero should not be enough to cause an implosion; however, subsequent mean field theories have been proposed to explain it.

Because supernova explosions are also preceded by an implosion, the explosion of a collapsing Bose–Einstein condensate was named "bosenova", a pun on the musical style bossa nova.

The atoms that seem to have disappeared almost certainly still exist in some form, just not in a form that could be accounted for in that experiment. Most likely they formed molecules consisting of two bonded rubidium atoms. The energy gained by making this transition imparts a velocity sufficient for them to leave the trap without being detected.

Current research

Compared to more commonly encountered states of matter, Bose–Einstein condensates are extremely fragile. The slightest interaction with the outside world can be enough to warm them past the condensation threshold, eliminating their interesting properties and forming a normal gas. It is likely to be some time before any practical applications are developed.

Nevertheless, they have proven useful in exploring a wide range of questions in fundamental physics, and the years since the initial discoveries by the JILA and MIT groups have seen an explosion in experimental and theoretical activity. Examples include experiments that have demonstrated interference between condensates due to wave-particle duality,[14] the study of superfluidity and quantized vortices,[15] and the slowing of light pulses to very low speeds using electromagnetically induced transparency.[16] Vortices in Bose–Einstein condensates are also currently the subject of analogue gravity research, studying the possibility of modeling black holes and their related phenomena in such environments in the lab. Experimentalists have also realized "optical lattices", where the interference pattern from overlapping lasers provides a periodic potential for the condensate. These have been used to explore the transition between a superfluid and a Mott insulator,[17] and may be useful in studying Bose–Einstein condensation in fewer than three dimensions, for example the Tonks-Girardeau gas.

Bose–Einstein condensates composed of a wide range of isotopes have been produced.[18]

Related experiments in cooling fermions rather than bosons to extremely low temperatures have created degenerate gases, where the atoms do not congregate in a single state due to the Pauli exclusion principle. To exhibit Bose–Einstein condensation, the fermions must "pair up" to form compound particles (e.g. molecules or Cooper pairs) that are bosons. The first molecular Bose–Einstein condensates were created in November 2003 by the groups of Rudolf Grimm at the University of Innsbruck, Deborah S. Jin at the University of Colorado at Boulder and Wolfgang Ketterle at MIT. Jin quickly went on to create the first fermionic condensate composed of Cooper pairs.[19]

In 1999, Danish physicist Lene Vestergaard Hau led a team from Harvard University which succeeded in slowing a beam of light to about 17 metres per second and, in 2001, was able to momentarily stop a beam. She was able to achieve this by using a superfluid. Hau and her associates at Harvard University have since successfully transformed light into matter and back into light using Bose–Einstein condensates: details of the experiment are discussed in an article in the journal *Nature*, 8 February 2007.[20]

Some subtleties

One should not overlook that the effect involves subtleties which are not always mentioned. One may be already "used" to the prejudice that the effect really needs ultralow temperatures of 10^{-7} K or below, and is mainly based on the *nuclear* properties of (typically) alkaline atoms, i.e. properties which fit to working with "traps". However, the situation is more complicated.

Up to 2004, using the above-mentioned "ultralow temperatures", Bose–Einstein condensates had been obtained for a multitude of isotopes involving mainly alkaline and alkaline earth atoms (^{7}Li, ^{23}Na, ^{41}K, ^{52}Cr, ^{85}Rb, ^{87}Rb, ^{133}Cs and ^{174}Yb). Not astonishingly, condensation research was finally successful even with hydrogen, although with the aid of special methods. In contrast, the superfluid state of the bosonic ^{4}He at temperatures below the temperature of 2.17 K is *not* a good example of Bose–Einstein condensation, because the interaction between the ^{4}He bosons is simply too strong, so that at zero temperature, contrary to Bose–Einstein theory, only 8% rather than 100% of the atoms are in the ground state. Even the fact that the above-mentioned alkaline gases show bosonic, rather than fermionic behaviour, as solid state physicists or chemists would expect, is based on a subtle interplay of electronic and nuclear spins: at ultralow temperatures and corresponding excitation energies, the half-integer (in units of $\hbar$) total spin of the electronic shell and the also half-integer total spin of the nucleus of the atom are *coupled* by the (very weak) hyperfine interaction to the integer (!) total spin of the atom. Only the fact that this last-mentioned total spin is integral causes the ultralow-temperature behaviour of the atom to be bosonic, whereas the "chemistry" of the systems at room temperature is determined by the electronic properties, i.e. is essentially fermionic, since at room temperature thermal excitations have typical energies which are much higher than the hyperfine values. (Here one should remember the spin-statistics theorem of Wolfgang Pauli, which states that half-integer spins lead to fermionic behaviour, e.g., the Pauli exclusion principle forbidding that more than two electrons possess the same energy, whereas integer spins lead to bosonic behaviour, e.g., condensation of identical bosonic particles in a common ground state.)

The ultralow temperature requirement of Bose–Einstein condensates of alkali metals does not generalize to all types of Bose–Einstein condensates. In 2006, physicists under S. Demokritov in Münster, Germany,[21] found Bose–Einstein condensation of magnons (i.e. quantized spinwaves) at room temperature, admittedly by the application of pump processes.

See also

- Atom laser
- Atomic coherence
- Bose gas
- Bose-Einstein correlations
- Electromagnetically induced transparency
- Fermionic condensate
- Gas in a box
- Gross-Pitaevskii equation
- Macroscopic quantum self-trapping
- Quantum vortex
- Slow light
- Superconductivity
- Superfluid
- Superfluid film
- Supersolid
- Tachyon condensation
- Timeline of low-temperature technology

- Tonks-Girardeau gas
- Super-heavy atom

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External links

- Bose-Einstein Condensation 2009 Conference [37] Bose-Einstein Condensation 2009 - Frontiers in Quantum Gases
- BEC Homepage [38] General introduction to Bose–Einstein condensation
- Nobel Prize in Physics 2001 [39] - for the achievement of Bose–Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates
- Physics Today: Cornell, Ketterle, and Wieman Share Nobel Prize for Bose–Einstein Condensates [40]
- Bose–Einstein Condensates at JILA [41]
- The Bose–Einstein Condensate at Utrecht University, the Netherlands [42]
- Alkali Quantum Gases at MIT [43]
- Atom Optics at UQ [44]
- Einstein's manuscript on the Bose–Einstein condensate discovered at Leiden University [45]
- The revolution that has not stopped [46] PhysicsWeb article from June 2005
- Bose–Einstein condensate on arxiv.org [47]
- Bosons - The Birds That Flock and Sing Together [48]
- Oxford Experimental BEC Group. [49]
- Cambridge University Cold Atoms Group. [50]
- Easy BEC machine [51] - information on constructing a Bose-Einstein condensate machine.
- Verging on absolute zero - Cosmos Online [52]

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