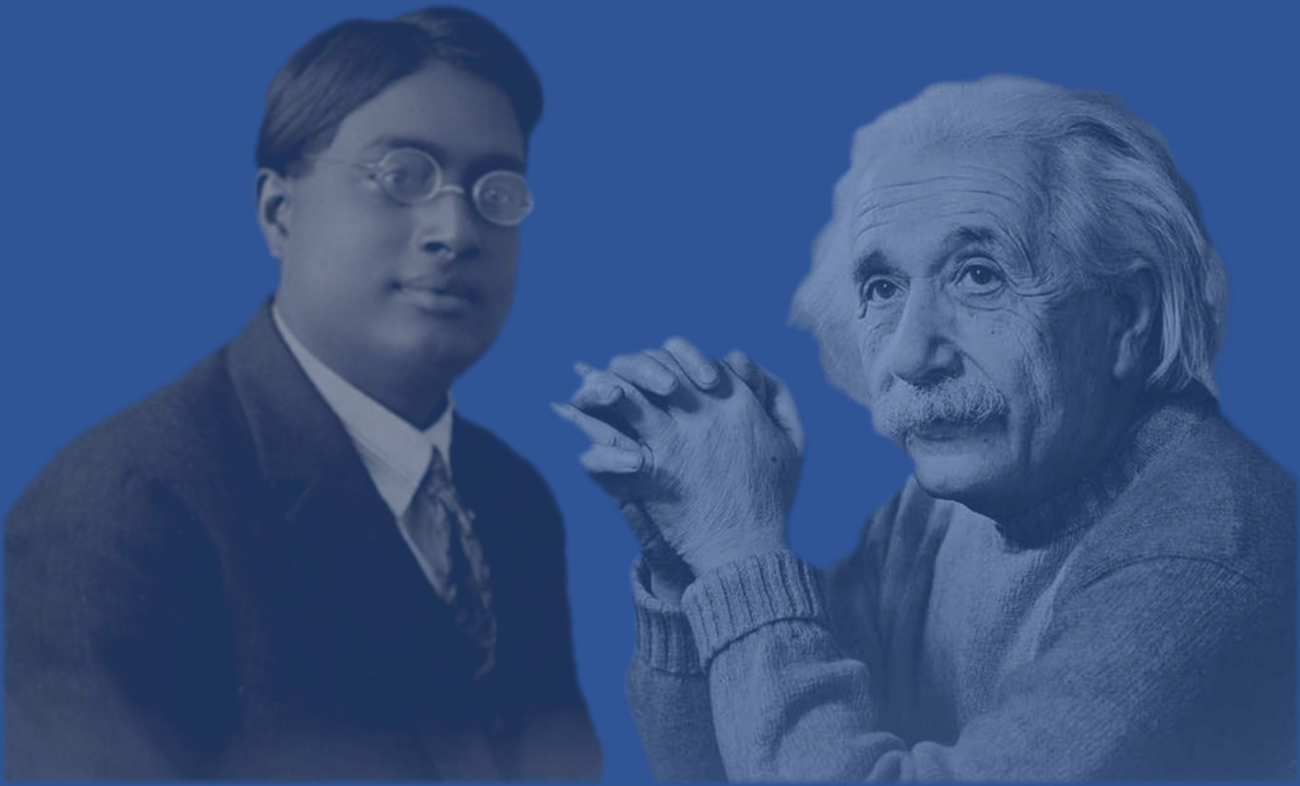


The Fifth State of Matter

Bose-Einstein Condensation and the 2001 Nobel Prize

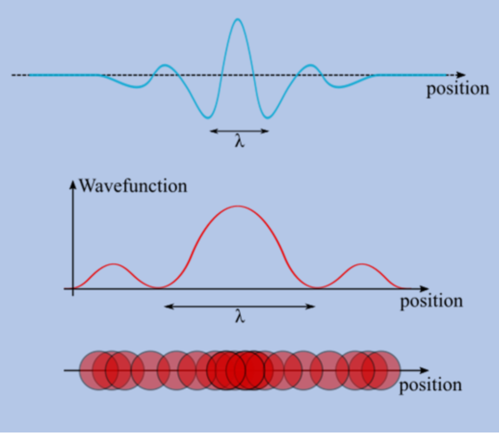
2759 words

In the June of 1924, Albert Einstein, the most esteemed physicist of his time, received a letter from an unknown Indian scientist: Satyendra Nath Bose, in which Bose asked for his paper on an alternative derivation for Plank's Law of Blackbody Radiation to be translated into German and published in Europe [1]. Einstein realised that Bose's technique of treating photons as a gas of identical particles could be generalised to model a gas of identical particles of conserved number, what Einstein labelled "the quantum theory of an ideal gas". Within the year, Einstein published 3 more papers extending Bose's work, the last of which predicted a new state of matter, one which would take 70 years to be created, winning its creators a Nobel prize [2].

At school it is commonly taught that there are four states of matter: solid, liquid, gas and plasma. That every substance exists in one of these states depending on its temperature and that a substance's properties depend on its state. However, what isn't taught until university physics is that a fifth state of matter can be created: a Bose-Einstein Condensate (BEC), formed by cooling a gas to extremely low temperatures. In this state, relatively large numbers of atoms start behaving like a single quantum object, in effect creating a 'super-atom'.

In order to properly explain Bose-Einstein condensates a few principles of quantum mechanics must first be introduced. Firstly, the family of particles known as bosons, named in honour of Satyendra Bose. All quantum objects, be it fundamental particles or atomic nuclei, are categorised into two families: fermions and bosons depending on their spin. The complexities of spin go far beyond the scope of this article, but it can be thought of as a positive number (e.g.,$0, \frac{1}{2}, 1, \frac{3}{2}$) which describes the angular momentum of a particle. This use of a number to describe a fundamental property of particle works in exactly the same way as something like electric charge. The spin of a particle must be either an integer (i.e.,$0, 1$), classing the particle as a boson, or a half-integer (i.e.,$\frac{1}{2}, \frac{3}{2}$), classing it as a fermion [3]. The bosons that are fundamental particles are related to forces such as the photon, the particle of light which carries the electromagnetic force, or alternatively the famous Higgs Boson which is a necessary component of why things have mass and interact with gravity. However, the right combination of half-integer fermions can create a composite particle with an overall integer spin resulting in larger bosons. An example of these composite bosons are even-mass number elements where the fermionic neutrons and protons combine to create overall bosonic atoms such as Helium-4.

The next principle to be understood is that of discrete energy levels. In classical physics, energy is continuous, the energy of an object can exist anywhere along a range – but this is not the case in quantum physics. Energy is quantised (hence the name *quantum* physics) and must take one of a fixed set of values, similar to how spin must take an integer or half-integer value. The lowest energy level, the



Wave-Particle Duality

Quantum particles often behave more like waves than particles. The blue line shows a water wave with a wavelength (size) λ. Similarly, the wavefunction of a particle (the probability of finding it at any one position) is spread out over space with a de Broglie wavelength λ, as shown by the red line. One interpretation of this is that the particle itself is spread out over space.

Credit: Me

ground state, is often non-zero meaning that those particles must always have some energy.

A third principle of quantum mechanics to be aware of is indistinguishability. Bosons and fermions both happen to be families of indistinguishable particles, which means that it is impossible to tell apart two of the same type of particle, one electron is identical to another electron. In other words, if two indistinguishable particles in a system were to be swapped, nothing about the system would change. Interestingly, the principle of indistinguishability implies that no more than two fermions can exist at the same energy level of a system (the two comes from technicalities about the spin of fermions), something known as the Pauli exclusion principle. An example of this is electron shells around atoms, electrons exist in 'shells' (energy levels) around atoms but no more than two electrons can exist in the same shell. However, theoretically, any number of bosons can exist at the same energy level, they are not subject to the Pauli exclusion principle.

The above principles can be combined to understand Bose-Einstein condensates. The family of particles with integer spin, known as bosons, have the capability to exist at the same energy level as other bosons. Theoretically, a collection of bosons could have enough energy sucked out of them to all exist at the ground state together, creating a Bose-Einstein condensate. There are a number of conditions that need to be satisfied in order for the BEC state to be produced such as the Yang criterion and the Penrose-Onsager criterion which will not be explained here. Two other general conditions are that the particles comprising the BEC must be weakly interacting i.e., there must be little to no force acting between individual particles, and that the de Broglie wavelength of the particles must be larger than the mean particle spacing, that is the 'edges' particles overlap with each other. The edges is in quotes because at the quantum level concepts like a particles having a defined edge stop making sense. This means that there is no distinction between the individual particles that make up a substance and instead the whole substance starts to behave like a single quantum entity.

Indistinguishability

Imagine a system of two particles, particle A and particle B. It can be described using a mathematical object called a wavefunction, written $\Psi(A,B)$ using the Greek letter *Psi* pronounced *sigh*. The amplitude squared of the wavefunction, $|\Psi(A,B)|^2$, gives the probability of the particles being in certain positions when the system is observed. If the indistinguishability principle is applied, the system must be observed to be the same when both particles are swapped i.e.,

$$|\Psi(A,B)|^2 = |\Psi(\mathrm{B},\mathrm{A})|^2.$$

Taking the square root of both sides gives

$$\Psi(A,B) = \pm\Psi(B,A),$$

revealing that in order for the indistinguishability principle to be upheld, the wave function is either the same after swapping particles, $\Psi(A,B) = +\Psi(B,A)$, or the wave function is negated, $\Psi(A,B) = -\,\Psi(B,A)$. It turns out that the former represents the wave functions of bosons and the latter the wave functions of fermions [3].

Next, imagine that these two particles can exist at one of two energy levels: the ground state, $\psi(0)$, or the next energy level up, $\psi(1)$. If both particles A and B are placed at the ground state, the overall wavefunction of the whole system looks like

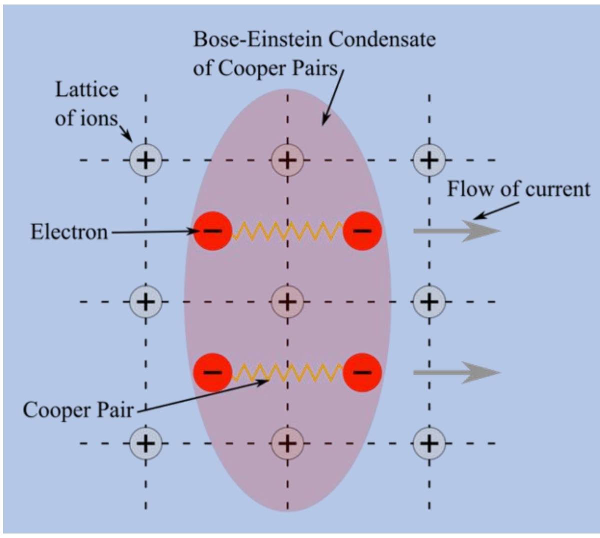
$$\Psi(A,B) = \psi_A(0)\psi_B(0) = \psi_B(0)\psi_A(0),$$

which remains the same when particles A and B are swapped. The same is true if both particles were placed at energy level 1,

$$\Psi(A,B) = \psi_A(1)\psi_B(1) = \psi_B(1)\psi_A(1).$$

Thus, a configuration of particles with both particles at the same energy level is possible for bosons but impossible for fermions.

Imagine raindrops falling on a windscreen, if the size of each raindrop is smaller than the distance between drops, the raindrops remain distinct from each other. If instead, for whatever reason, the distance between each raindrop on the windscreen became smaller the size of any raindrop, they would lose their distinctiveness and would instead become a single puddle. In the same way, when a substance becomes a Bose-Einstein condensate, the individual particles lose their



Superconductivity

The BCS theory explains superconductivity as electrons pairing up into Cooper pairs which themselves form a Bose-Einstein condensate which can flow through the lattice of positively charged ions without resistance. Since the BEC is negatively charged, it can continue to carry current.

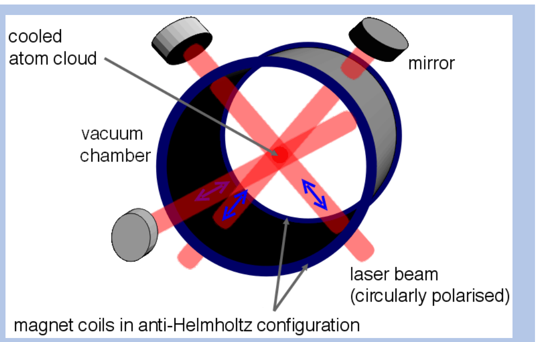
Credit: Me, inspired by Arvin Ash

distinctiveness, and the substance as a whole starts to behave like a single object. Mathematically, instead of a substance being described by a set of a wavefunctions, one for each particle, the whole substance is encapsulated by a single wavefunction. This means that BECs can sometimes display the properties of individual quantum objects at much larger scales than would be expected – exactly the property that interests scientists so much.

The characteristics of a Bose-Einstein condensate can be used to understand other bizarre low-temperature creations such as superfluidity and superconductivity. Superfluidity is when a liquid, upon being cooled enough, is found to have zero viscosity, viscosity being a liquid's resistance to flow [4]. Many examples of superfluidity are not considered to be pure BECs because they are not weakly interacting, one of the essential conditions, despite displaying the behaviours expected of a BEC.

The other example of superconductivity is a phenomenon that can explained using BECs under the Barden-Cooper-Schrieffer (BCS) theory of superconductivity [5]. Any normal metal can be thought of as a lattice (grid) of positively charged metal atom ions surrounded by a sea of their negatively charged electrons which have become disconnected from any single ion. Think children in a ball pit, the children being ions and the balls being electrons. What we observe as electricity flowing through a wire involves the electrons moving through this lattice of ions and as they do so they sometimes colliding with the ions, transferring some of their energy. This effect is observed as a heating caused by the resistance inherent to that wire, a household example might be how a laptop charging plug heats up as the laptop charges. However, in the right metal, at low enough temperatures this resistance effect disappears completely. The electrons pass through the wire as if it wasn't there, a property known as superconductivity. What makes superconductors so fascinating is the fact that they have a resistance of zero, not negligibly small but exactly zero. At first it isn't clear how BECs are related to superconductivity as electrons are fermions but BECs are made up of bosons, but the BCS theory makes the connection through Cooper pairs. A phenomenon wherein two electrons at ground state energy, flowing through a metal, become conjoined by electromagnetic effects beyond the scope of this article. As alluded to earlier, two fermions with half-integer spin (the two electrons) can combine to create a quantum object (the Cooper pair) with integer spin becoming a boson. All of these bosonic Cooper pairs flowing through a superconductor can all inhabit the lowest allowed energy level together and start to behave like a single negatively charged Bose-Einstein Condensate. As each Cooper pair is in its lowest possible energy level it cannot collide with an ion and transfer some energy since it has no more energy to give. The electrons can get away with never colliding with any ions because they have all become part of this larger BEC which doesn't have to interact with the ions. This explanation also gives two reasons why superconductors can only exist at such ultra-low temperatures: firstly, Cooper pairs are incredibly delicate meaning that it only takes a small amount of heat to destroy them all and secondly, all the electrons need to be in their lowest energy states in order to form the BEC, a small amount of heat would bump the electrons up to higher energy levels destroying the BEC.

Bose-Einstein condensates can only exist at extremely low temperatures which poses some monumental challenges to the scientists who wish to create them. The field of experimental cold matter physics took off in the early 1970s with the invention of the laser. Normally lasers are used for heating but if a photon the exact right frequency (the transition frequency) collides with an atom, the atom will absorb the photon. Due to conservation of momentum this slightly reduced the speed of the atom in the direction of the light. The absorbed photon is then emitted in a random direction at some later time. As this happens many times, the momenta from the remission of photons in all directions cancel out and the atom remains slowed down in the direction of the laser. If the laser's frequency is tuned to be slightly lower than the transition frequency the Doppler effect means that only the atoms moving directly towards the laser source experience the correct frequency to absorb the photon. This enables a high degree of control over which speed of atoms actually get slowed down by the laser. Since the speed of atoms dictates the temperature of the substance, when the atoms are slowed, the temperature of the whole substance decreases slightly. Using three lasers pointing along the x-y-z directions so that an atom moving in any direction experiences the slowing effect is known as the Doppler Cooling technique, one of the most important tools in the cold-matter physicists toolbox [6].



A magneto-optical trap (MOT), used for cooling vapours to ultra-low temperatures.

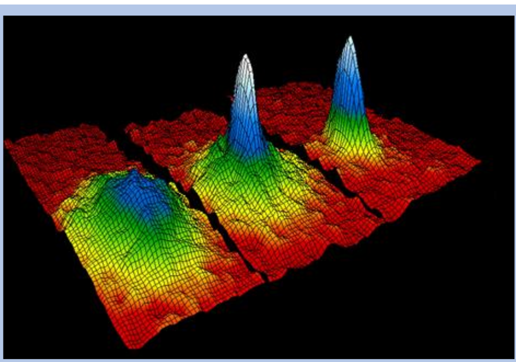
Credit: Jan Krieger, Wikimedia

Another tool essential to the field known as magnetic trapping uses magnets to suspend a collection of atoms inside a chamber. Extremely cold atoms happen to also be extremely sticky, if a very low energy gas atom collides with the wall of its container it will stick there. So, ultra-low temperature atoms must be held away from all surfaces by magnets. Combining magnetic trapping systems with Doppler cooling techniques results in a device called a Magneto-Optical Trap (MOT), a standard instrument in experiment cold matter physics and the first step in creating BECs.

It turns out that a MOT on its own can't quite create low enough temperatures and high enough densities for BECs to form, another cooling technique is needed: evaporative cooling, essentially a more sophisticated version of what happens to a cup of hot coffee. In the coffee, there are atoms bouncing around with a range of velocities with some of the atoms being fast enough to escape the liquid and evaporate away. The remaining atoms then have a slightly lower average speed and thus a

Doppler Effect

A wave coming from a moving object or experienced by a moving observer appears to have a shifted frequency, the amount of the shift depending on the speed of motion. A common experience of this effect in sound waves is the change in pitch of an ambulances siren as it drives past. This effect can also happen with light waves, the change in frequency resulting in a change in colour of the light.



Velocity distribution with position of rubidium atoms, going from just before condensation (left) to just after (right). High peaks correspond to large numbers of atoms.

Credit: NIST/JILA/CU-Boulder

slightly lower temperature. As this happens repeatedly, the hot cup of coffee evaporates and cools down to room temperature. In evaporative cooling techniques, a sample of ultra-cold atoms are suspended by magnets with some of the fasting moving atoms allowed to escape the sample. Using advanced techniques involving electron spin resonance, the exact speed at which an atom escapes can be regulated resulting in finely controlled cooling down to microkelvin temperatures (millionths of a degree above absolute zero).

Physicist Carl Wieman first drew up guidelines on how a BEC could be formed around 1990. While at the University of Colorado, Boulder, he, alongside his postdoc researcher then colleague Eric A. Cornell, managed to finally form a true Bose-Einstein condensate in their lab in 1995. Also in 1990, across the US at MIT, physicist David E. Pritchard, who pioneered some of the cooling techniques mentioned above, introduced postdoc researcher Wolfgang Ketterle to the faculty. A few months after the Boulder team, Ketterle's team was also able to produce BECs, they then went on to investigate its properties and managed to create an 'atom laser' [7].

Both teams started with a vapour of alkali atoms suspended in a near vacuum magneto-optical trap. After being cooled as much as possible the sample was then transferred, while still in a vacuum, to another device to be cooled via evaporative cooling. In order to observe the sample, the magnetic trap was turned off and the atoms allowed to expand away from each other. They were then flashed by a laser, the absorption of the light by the atoms casting a 'shadow' onto a camera which was used to calculate the behaviour of the atoms. Wieman and Cornell's team used a vapour of Rubidium-87 which they able to cool around 2000 atoms of to 20 nanoKelvins (billionths of a degree above absolute zero) [8]. Ketterle's team used Sodium atoms to create a BEC of around 500'000 atoms, enough to start actively investigating its properties [9]. For their work, Wieman, Cornell and Ketterle were all awarded the 2001 Nobel Prize by the Royal Swedish Academy of Sciences.

The successful creation of Bose-Einstein condensates opens the door to exciting new areas of research. Atomic physics has traditionally only dealt with individual atoms but BECs allow the precision of atomic physics experiments to be applied to many-body systems. It is highly unlikely that BECs exist anywhere in the universe, but this does not detract from the enthusiasm for the field – physicists tend to be less interested in what does exist and more interested in what can exist.

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