

States of Matter – Part II. The Three Additional States: Plasma, Bose-Einstein Condensate and Fermionic Condensate

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Abstract

This is a continuation of Part I, and contains descriptions of the three additional states of matter: Plasma, Bose-Einstein Condensates (BEC) (discovered by Ketterle, Cornell and Wiemani in 1995) and Fermionic Condensates (discovered by Jin in 2003). Plasma consisting of ions and electrons exists at high temperatures beyond the gas state; and the two condensates, Bose-Einstein and Fermionic, exist at temperatures close to absolute zero. The former is composed of boson particles that obey the Bose-Einstein particle statistics; and the latter is made up of Fermion particles that obey the Fermi-Dirac particle statistics.

Most of today's cutting-edge technologies -- smaller, faster computer chips, micro-electro-mechanical systems (MEMS) and quantum computers -- are positioned in the twilight zone between the quantum and macroscopic worlds. BECs are big enough visible quantum creatures, so BECs are in a position to advance these technologies and discover others in future.

Keywords: *Ions, electrons, particle statistics, plasma, boson particles, Fermi-Dirac particle, micro-electro-mechanical systems*

Additional States

The Plasma State

Plasma, shown in Fig. 8, is the fourth state of matter. This state was discovered in 1879 by Sir William Crookes in England, but its application was delayed until 1929 when Irving Langmuir, an American chemist and physicist, used it to obtain fluorescent light. However Hannes Alfvén (1908-1995), a Swedish physicist, is considered the father of modern day *plasma science*. He received the Nobel Prize in 1970 for his contributions to basic plasma physics and for his studies of space plasmas (Vu *et al.*, 2004).

Plasma occurs abundantly in the universe. More than 99% of all visible matter in the universe is in the plasma state. Plasma appears on earth only in places like lightning bolts, flames, auroras, and fluorescent lights. Natural plasma exists only at very high temperatures, or low temperature vacuums. Artificial plasma can be created by using electrical charges on gases (Kasinar 2004).

As shown in Fig. 10, matter changes state as it is exposed to different physical conditions. Ice is a solid with H₂O molecules arranged in definite regular patterns. When ice melts its pattern changes into the liquid state pattern and water is formed. As the water is warmed the molecules separate further to form steam. On heating steam further, it may be ionized. If heated sufficiently, repeated ionization occurs and creates clouds of free electrons and positive ions. But some are left intact without being ionized. This mixture of ions, electrons, and neutral atoms is plasma. However, a collective response to electric and magnetic fields may be observed only when sufficient numbers of charged particles are present. In other words *plasma density* must be sufficient.

On the microscopic scale, plasma contains electrons and ions and, therefore, conducts electricity. But on the macroscopic scale, it is neutral as the number of electrons and positive ions in the whole system are equal. The charged plasma particles are propelled by external electric and magnetic fields. This motion of the particles generates

magnetic fields and electric currents from within the plasma, as shown in Fig. 9. A complex set of interactions between the external applied fields and the internal motion-induced fields is set up. This makes plasma unique (NASA 2003).

Scientists study plasma for practical purposes. In an effort to harness fusion energy on earth, physicists are studying devices that create and confine very hot plasmas in magnetic fields. In space, plasma processes are largely responsible for shielding earth from cosmic radiation, and much of the sun's influence on earth occurs by energy transfer through the ionized layers of the upper atmosphere.

Bose-Einstein Condensate (BEC)

The Bose-Einstein condensate is the fifth phase of matter, which is formed by cooling matter to near absolute zero (Fig. 11). BECs were predicted by Satyendra Nath Bose in the 1920s.

The Bose-Einstein Condensates are made up of bosons (particles that obey Bose-Einstein particle statistics) and consists of thousands of ultra-cold particles that occupy a single quantum state. At temperatures near absolute zero the behavior of atoms depends on their “spin” or intrinsic angular momentum. Bosons have integral spins (integer values in units of $h/2\pi$ - the Planck constant h divided by 2π). For bosons there are no restrictions such as the Pauli Principle¹. Thus bosons can all collapse into the same quantum ground state.

This process, called Bose-Einstein condensation, is the basis of *superconductivity* – free (no resistance) flow of electric current (Rodgers and Dume 2004). Based on Bose's work, Albert Einstein developed rules for deciding when two photons should be counted up as either identical or different, and generalized the results in what is known as *Bose-Einstein statistics*. It is a description of the statistics of identical particles that can share a given quantum energy level. The existence of *stimulated emission* of photons, the basis of *quantum electronics* (lasers), was one important prediction of Bose-Einstein statistics.

¹ See under Fermion Condensate

Einstein applied the statistics to atoms also (instead of photons) and discovered that all atoms tend to drop into the lowest accessible energy level at a certain very low temperature. The *Heisenberg Uncertainty Principle* (HUP), which says that it is impossible to know both a particle's velocity and its position simultaneously with certainty, facilitates understanding of the phenomena. When atoms are cooled to a low enough temperature they have only a limited number of low energy quantum states available. Consequently, their velocities become more definite. In accordance with HUP, this causes their positions to ‘smear out’ (Fig. 12), effectively causing the individual atoms to overlap each other.

Bose-Einstein condensates BECs are indescribable by ordinary words because they are from another world - the world of *quantum mechanics*, which reveal the bizarre rules of light and matter on atomic scales. On that scale matter can be in two places at once; objects can behave as both particles *and* waves; and everything is uncertain. Probability is the key factor in the quantum world.

Quantum rules are counter to intuition but they are the basics of macroscopic reality. Bose-Einstein condensates form a bridge between the quantum and the macroscopic worlds. They obey the laws of the small while they intrude on the big. They are big enough visible quantum creatures. Most of today's cutting-edge technologies -- smaller, faster computer chips, micro-electro-mechanical systems (MEMS) and quantum computers are positioned in the twilight zone between the quantum and macroscopic worlds. BECs will advance these and discover others.

BECs form when gas atom behavior changes from ‘flying billiard balls’ of classical physics to behaving as one giant matter-wave of quantum mechanics (Fig. 16). At normal temperatures gas atoms behave as ordinary particles (e.g. billiard balls). Although wave and particle aspects of matter are always present together (wave-particle dualism²), the particle

² Wave-particle dualism, described mathematically by the de Broglie equation $\lambda = h/mv$, says that matter has both wave and particle characteristics. Particle and wave are the same with different emphasis, just like the two sides of a coin.

aspect is dominant here. As the temperature is lowered the particle aspect dims and the wave aspect starts to grow in accordance with the de Broglie equation $\lambda = h/mv$. Lower still; a critical temperature is reached where matter waves start to overlap. Then at temperatures close to absolute zero, a giant matter wave is formed – BEC is produced.

Bosons being copy-cats tend to copy their neighbor's motion. The particles behave like a huge single super-atom with all of its many overlapping constituent atoms sharing a single quantum state. Contact with the outside world raises the temperature above the condensation threshold. Thus, BECs are extremely fragile. Practical applications will indeed take time (Singapore Science Centre 2004).

Fig. 13 shows the emergence of a Bose-Einstein condensate. The atoms behave like a conventional gas with a conventional smooth distribution curve of high and low energy atoms, at 400 nK. At 200 nK BEC begins to appear as a peak, in the form of a significant fraction of near-zero energy atoms. The remaining non-condensed atoms appear as a skirt surrounding the peak. At lower temperatures (50 nK) almost the entire non-condensed fraction has vanished. Only about 3000 atoms in a single macroscopically occupied wave-function are left. A BEC consists of a group of a few million atoms merged to form a millimeter sized matter-wave.

Ketterle created BECs in 1995 by cooling a gas of sodium atoms to a few hundred billionths of a degree above absolute zero.³ At these low temperatures atoms behave more like waves than particles. Laser beams and magnetic traps hold the atoms so that they overlap and form a single giant matter wave.

Those atoms that contain an even sum of nucleons (neutrons, protons and electrons) can form BECs. For example the sum of neutrons, protons and electrons in sodium is 34, an even number. Hence sodium can form BECs. Atoms or isotopes with odd sums cannot form BECs (Wanwisa *et al.*, 2004).

Eric Cornell (National Institute of Standards and Technology) and Carl Wieman (University of Colorado) also created BECs in 1995. They used super-cold rubidium atoms.

³ More than a million times cooler than interstellar space!

The condensate was formed inside a small glass cell surrounded by a tabletop array of magnets, lasers and computers. Cornell and Wieman shared the 2001 Nobel Prize with Ketterle (Wanwisa *et al.*, 2004).

Fermionic Condensate

Fermionic atoms at low temperatures form the Fermionic Condensate, which is a superfluid phase⁴. It is similar to the Bose-Einstein condensate but fermionic condensates are formed from fermions instead of bosons. Fermions form condensates just like electrons form a superconductor. The first fermionic condensate was created in 2003 by a team from the Joint Institute for Laboratory Astrophysics (JILA) led by Deborah S. Jin (Rodgers and Dume 2004; Wikipedia 2004). Fig. 14 shows constant energy surfaces of a free Wilson fermion (Flynn 2000).

Jin used potassium-40 gas atom fermions in an optical trap at a temperature of about 300 nK. A magnetic field was applied to create a “Feshbach resonance”, which changes the inter-atomic interaction from being highly repulsive to highly attractive. Careful control of the magnetic field makes the atoms form Cooper pairs rather than molecules (Rodgers and Dume 2004).

More descriptively, the process was explained as follows: “A gas of 500,000 potassium atoms was cooled to temperatures below 50 billionths of a degree Celsius above absolute zero (-459°F) and then a magnetic field was applied near a special ‘resonance’ strength. This magnetic field coaxed the fermion atoms to match up into pairs, akin to the pairs of electrons that produce superconductivity, the phenomenon in which electricity flows with no resistance. The Jin group detected this pairing and the formation of a fermionic condensate for the first time on Dec. 16, 2003” (The Nation 2004).

⁴ Superfluids possess some properties that do not appear in ordinary matter. For instance, they can flow at low velocities without dissipating any energy at all. At higher velocities, energy is dissipated by the formation of quantum vortices that act as “holes” in the medium where superfluidity breaks down.

Fig. 14 shows images of a condensate formed from fermion potassium atom pairs (Vu *et al.* 2004). Atom density increases upwards, and attractive force in fermion pairs increases left to right, in response to increases in magnetic field strength. Thus higher peaks indicate a higher condensate formation. And the formation is seen to be directly dependent on the applied magnetic field.

Unlike bosons that have integral spins, fermions have half-integral spins of 1/2, 3/2, 5/2.... Thus unlike bosons, fermions are restricted by the Pauli Exclusion Principle and no two fermions can occupy the same quantum state. They are therefore loners rather than copy-cats like the bosons (Fig. 17).

Electrons are fermions and they form Cooper pairs⁵. This will make it possible to further understand superconductivity.

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Conclusion

Apart from the three common states of matter, solid, liquid and gas, there are three additional states, plasma, Bose-Einstein condensate (BEC) and Fermionic condensate. Plasma is obtained by drastic heating of a gas; whereas BEC and Fermionic condensate are obtained by going in the opposite direction – drastic cooling to near absolute zero temperatures.

⁵ Named after Leon Cooper of the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity

Development of applications of the condensates will take time. Currently they are of academic interest and serve only for unlocking nature's mysteries. One day applications may arise just like in the case of superconductors that ultimately will allow transmission of electricity without resistance.

With its basic idea of states of matter, chemistry has supplied knowledge to create a better world. Many more states may be discovered by using just the same trends of extreme increase or decrease in temperatures.

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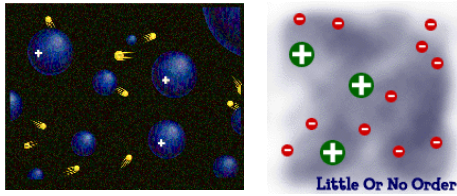


Fig. 8. Microscopic illustration of plasma



Fig. 9. Plasma generating fields

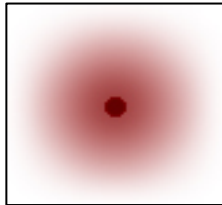


Fig. 11. Bose-Einstein Condensate

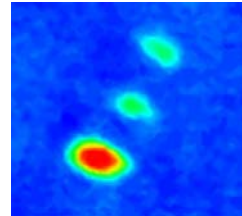


Fig. 12. Smearred fuzzy position

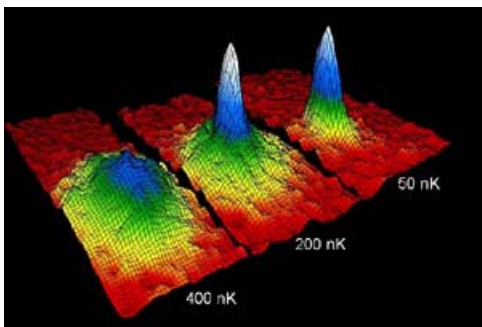


Fig. 13. Emergence of BEC

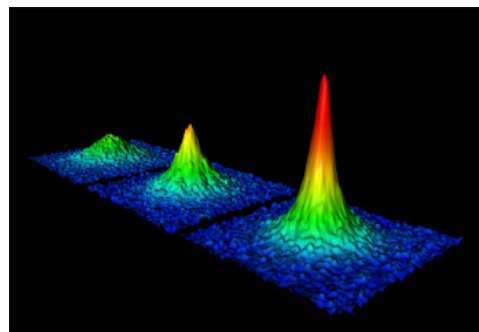


Fig. 14. Emergence of Fermionic Condensate





Solid	Liquid	Gas	Plasma
Example: Ice H ₂ O	Example: Water H ₂ O	Example: Steam H ₂ O	Example: Ionized Gas H ₂ → H ⁺ + H ⁺ + + 2e ⁻
Cold T < 0°C	Warm 0 < T < 100°C	Hot T > 100°C	Hotter T > 100,000°C > 10 electron Volts
			
Molecules Fixed in Lattice	Molecules Free to Move	Molecules Free to Move, Large Spacing	Ions and Electrons Move Independently, Large Spacing

Fig. 10. Solid, Liquid, Gas and Plasma

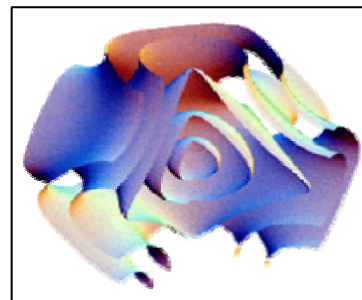


Fig. 15. Constant energy surfaces in the Brillion zone for a free Wilson fermion

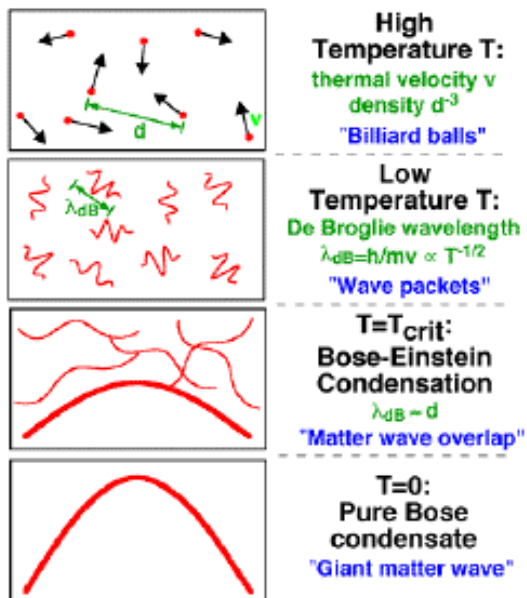


Fig. 16. Transition to a BEC

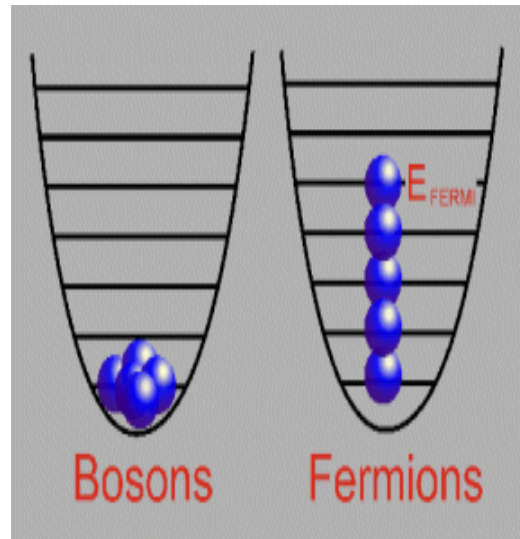


Fig. 17. Bosons all occupy the lowest quantum level together and form a BEC. Being restricted by the Pauli Principle, Fermions occupy different quantum levels.