The International Journal of Engineering and Science (IJES)
|| Volume || 7 || Issue || 10 Ver.III || Pages || PP 45-49 || 2018 ||
ISSN (e): 2319 – 1813 ISSN (p): 23-19 – 1805

What Is Bose-Einstein Condensate?

Levada[1], C. L.; Maceti[2], H.; Lautenschleguer[3], I.J.;Vicente[4], A.
[1 2 3]Science Teaching Group of the Herminio Ometto Foundation – Brazil
[2 4] Science Teaching Group of the Colégio Puríssimo Coração de Maria – Brazil
Corresponding Author: Levada

---***ABSTRACT***---

When a gas is cooled to very low temperatures, it is possible to achieve a regime where its behavior ceases to be classical. In this way, the traditional view we have of a gas as consisting of particles of a disordered motion is no longer maintained. If the gas particles are of the boson type, the state reached in the regime of ultra-low temperature, culminates in the formation of a new phase called Bose-Einstein Condensation (BEC). This name was chosen due to the fact that this state was initially predicted by Albert Einstein in 1925 using for this the theoretical bases contained in the work of the scientist Nath Bose. This theory was largely responsible for the choice of Nobel awards in the years 2001 and 2012; and despite this, Bose was never awarded or duly recognized for his work.

KEYWORDS-*Bose-Einstein, Condensation, statistics*

Date of Submission: 12-10-2018 Date of acceptance: 27-10-2018

I. INTRODUCTION

The Bose-Einstein condensates were first predicted theoretically by Satyendra Nath Bose, an Indian physicist who also discovered the subatomic particle named in his honor, the boson. Bose was working on statistical problems of quantum mechanics and sent his ideas to Albert Einstein. Einstein considered them important enough to publish them. As important as this, Einstein saw that Bose's mathematics - later known as Bose-Einstein statistics - could be applied to both atoms and light. In this work, the young Bose presented a deduction of the Planck formula for the distribution of energy by the different frequencies of the spectrum of the thermal radiation. As Einstein had done with regard to the photoelectric effect, Bose described the radiation as being a particulate gas. However, he introduced a completely new way of enumerating the possible states of these particles. Einstein took an interest in the work, translated it into German, and recommended its publication in the journal Zeitschriftfür Physik. Bose's statistical treatment of the problem of blackbody radiation, treating light as solid corpuscles that do not interact, opened the door for Einstein to predict a behavior of matter at a certain critical temperature density known as Bose-Einstein Condensate. This state became known as the fifth state of matter. The Bose-Einstein condensate - often referred to as the "fifth state of matter" is obtained when a set of atoms has their temperature cooled almost to absolute zero. In these conditions, the particles no longer have free energy to move relative to each other, and some of them, called bosons, begin to share the same quantum states, thus becoming indistinguishable. Thus, they obey the so-called Bose-Einstein statistics, applied to identical particles. In the Bose-Einstein condensate, the particles behave as if they were a single particle. Bose-Einstein condensates are low temperature fluids with properties not fully understood, such as flowing spontaneously out of their container. This effect is a consequence of quantum mechanics, which postulates that any system can only acquire energy in discrete quantities. If a system is at such a low temperature that it is in its minimum energy state, it is not possible to reduce its energy, not even by friction. Thus, without friction, the fluid easily overcomes gravity due to the adhesion forces between the fluid and the wall of its container and will take the most favorable position, that is, all around the container. One of the great discoveries of statistical physics was the Bose-Einstein condensation, which in a simplistic way can be understood as the tendency of the constituents of a gas of bosons in occupying their lower state of energy at low temperatures.

II. THE BOSE-EINSTEIN DISTRIBUTION

The Bose-Einstein distribution, BE, describes the statistical behavior of identical and indistinguishable particles, called bosons, that do not obey the Exclusion Principle, that is, they have whole spin. At low temperatures, bosons can behave quite differently from fermions, because an unlimited number of them can accumulate in the same state of energy, a phenomenon called "condensation." A BE gas obeys the following law:

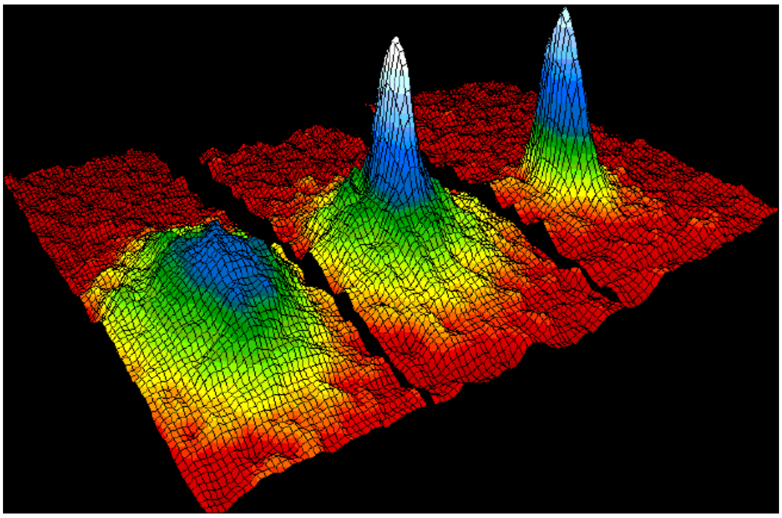
$$\boxed{f_{BE}(E,T,\mu) = \frac{1}{\exp\left(\frac{E-\mu}{kT}\right)-1}}$$ CENTRALIZE

which is the Bose-Einstein distribution, which specifies the mean (or probable) number of bosons in the energy state E of a system in thermal equilibrium. The symbol k indicates the Boltzmann constant, while T is the temperature, and μ is the chemical potential of the gas.

In the comparison of partition functions for distinguishable and non-distinguishable particles a useful parameter is the so-called mean number of occupancy for each energy state, that is, the number of particles occupying a given quantum state of energy. Considering that the particles are indistinguishable it makes no sense to say that a particle is in such a state, that is, it makes no sense to ask what individual state a particular particle is occupying. Thus, the quantum state is fully specified by the set n_j of particles that occupy the energy state ε_j, that is, the only relevant information is to know how many identical particles are occupying a given state. For the case of the bosons the value of the average number of occupancy is obtained by

$$n_k = \frac{1}{e^{\beta(\varepsilon_k-\mu)}-1} \quad , \sum_k n_k = N \quad , \beta = {}^{1}\!/_{k_B T}$$

On July 14, 1995 issue of Science magazine, researchers from JILA reported achieving a temperature far lower than had ever been produced before and creating an entirely new state of matter predicted decades ago by Albert Einstein and Indian physicist Satyendra Nath Bose. Cooling rubidium atoms to less than 170 billionths of a degree above absolute zero caused the individual atoms to condense into a "superatom" behaving as a single entity.



` Figure1- Cooling rubidium atoms to less than 170 billionths of a degree above absolute zero .The graphic shows three-dimensional successive snap shots in time in which the atoms condensed from less dense red, yellow and green areas into very dense blue to white areas. JILA is jointly operated by NIST and the University of Colorado at Boulder.This image is in the **public domain** in the United States because it is a work of the United States Federal Government, specifically an employee of the National Institute of Standards and Technology, under the terms of Title 17, Chapter 1, Section 105 of the US Code.

III. EXPERIMENTAL ARRANGEMENT

In order to assemble the BEC experiment, first, some of the specific isotopes of atoms are chosen, which may be, for example, Helium, Sodium, Rubidium or Hydrogen, consisting of bosons that are purified and placed in a vacuum. Rubidium condensate is the most used for this purpose. The atoms are cooled to one degree Kelvin temperature therefore they must be practically immobile to remain in the base BEC state. Then they are placed in a magnetic trap, keeping them in a limited area. The magnetic trap is arranged with eight magnets in what is known as a quadrupole configuration. A laser with a precisely calculated wavelength focuses on atoms, and as light scatters away from the atoms, it carries with it more energy than it has brought in the process. The energy state of the atoms is, of course, directly related to the speed with which they are moving, so that the first wavelength used is selected for the fastest atoms present. The wavelength of the laser must be accurately adjusted to the atom.

One of the most difficult problems faced by physicists when performing BECs is to keep the laser tuned at the right frequency despite external interference. The atoms are then cooled through what is known as evaporative cooling. Essentially, evaporative cooling allows the faster and more energetic atoms to escape the trap, leaving behind only the slower and less energetic atoms. Since the early 1970s, there has been increasing interest on the part of experimentalists to find a Bose-Einstein condensate in a dilute gas at low temperature.

The first pure BEC was created only in 1995, when improved cooling and imprisonment techniques had been perfected. One of them is laser cooling, a technique that makes use of momentum transfer between a photon and an atom to reduce its velocity and cause cooling, which can take the atom to the required temperature for Bose-Einstein condensation to occur. This made its developers Steven Chu, Claude Cohen-Tannoudji, and William Phillips win the 1997 Nobel Prize in Physics.

Combining laser cooling and evaporative cooling techniques, scientists were able to succeed in reaching temperature and density required to form the BEC. This BEC was created from an arrangement of magnets, lasers and computers in a laboratory of the Joint Institute Laboratory for Astrophysics (JILA). Starting with a gas, initially at room temperature, the researchers braked the atoms with laser, by absorbing photons with certain energy and the emission of photons with higher energy, and captured them in an optical trap. The lasers were aligned so as to bombard the atoms from any direction: from the front, from the back, from the right, from the left, from above and from below. The atoms are subjected to another cooling session, this time selecting the hottest ones and ejecting them from the trap. As the hotter atoms come out, carrying with them heat from the others, the weak interaction between the remaining ones allows the obtaining of a new temperature, now lower. The intensity of the trap is reduced, allowing less energy atoms to be ejected, and so on. This is the technique of evaporative cooling.

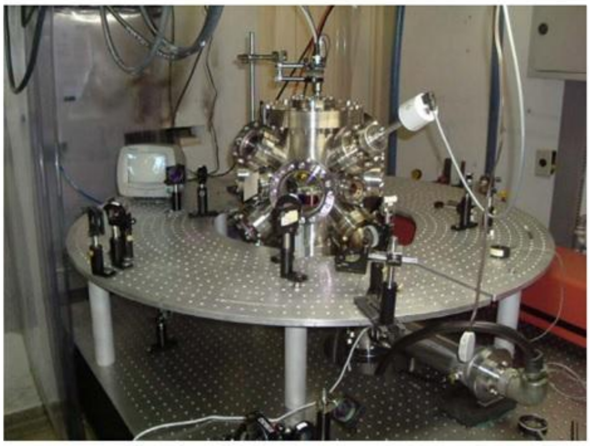


Figure2- Imprisonment Chamber Mounted on a Round Table
(Source:file:///C:/Users/pesquisa05/Downloads/CarlosMenegatti_M.pdf)

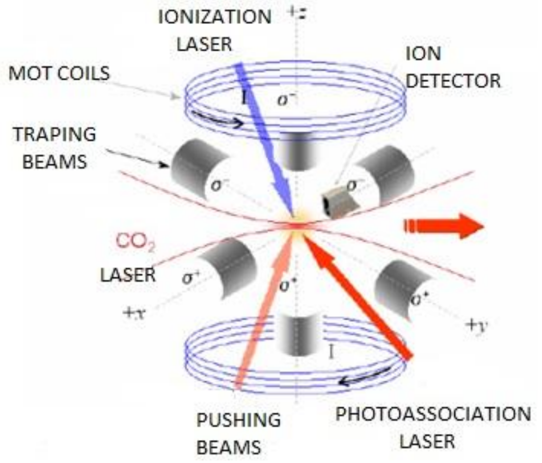


Figure 3 - Quantum Trap
(Source: file:///C:/Users/pesquisa05/Downloads/CarlosMenegatti_M.pdf)

IV. PAULI'S EXCLUSION PRINCIPLE IS NOT OBEYED

The occurrence of BEC is a macroscopic manifestation of the so-called quantum nature of matter. Other manifestations of this nature are the superconductivity and superfluidity of liquefied helium, and the latter has not yet found a convincing and complete theoretical explanation, although there is abundant evidence that it is associated with BEC.

Usually, atoms need to have definite energies - in fact, one of the foundations of quantum mechanics is that the energy of an atom or other subatomic particle cannot be arbitrary. That is why electrons, for example, have discrete "orbitals" they need to occupy and why they emit photons of specific wavelengths when they fall from one orbital, or energy level, to another. However, when atoms are cooled to within billionths of one degree of absolute zero some of these atoms begin to fall at the same energy level, becoming indistinguishable. That is why the atoms of a Bose-Einstein condensate behave like "super atoms". When one tries to measure where they are, instead of observing distinct atoms, one notices more a diffuse ball.

The other states of matter follow the Pauli’s Exclusion Principle quoted by physicist Wolfgang Pauli, one of the pioneers of quantum physics. He says that fermions, the types of particles that make up matter, cannot be in identical quantum states. That is why when two electrons are in the same orbital, their spins have to be opposites, so they add up to zero. This, in turn, is one of the reasons why chemistry works the way it works and why atoms cannot occupy the same space at the same time. Bose-Einstein condensates break this rule.

The properties of BEC are strange and not at all intuitive. One of the most surprising is superfluidity, or frictionless flow. The condensate has a collective rigidity that "protects" the particle-to-particle interaction processes responsible for the fluid viscosity or flow resistance, resulting in the superfluidity of the BEC. In fact, it is not only possible for the bosons to occupy the same quantum state; it is observed that the particles even have a tendency to accommodate themselves in this way. This tendency translates into the amplification by a factor $(N + 1)$ of the transition probability from an initial state of a particle to a final state occupied by N particles. Thus, for example, if during the flow of a condensate in a capillary tube one of the particles is dispersed by interaction with the walls of the tube, the probability of transiting back to the condensate is proportional to $(N + 1)$, where N is number of bosons that form the condensate. As this number is macroscopic, that is, huge, the particle immediately returns to the condensate with probability close to one.

V. HIGGS’ CONDENSATE

Finally, it is important to mention an important relation of this phenomenon of condensation to ultra-low temperatures, with the physics that occurs at the opposite extreme of the spectrum of energies. CERN put into operation in 2007/2008 one of the most complex and expensive physics devices, the LHC (Large Hadron Collider); some of the detectors used in the LHC are the size of a cathedral. The fundamental result has been expected from this accelerator is the undisputed detection of a very special particle, the Higgs boson. Now the standard model of particle physics states that the universe we live in is a condensate of the Higgs boson: the mean value of the respective quantum field is nonzero. The Higgs that CERN's experience expects to find is, of course, the excitation of the Higgs field around the finite value it has in the vacuum. The "original" bosons, defined from the null value of the field, exist in great quantity everywhere. Of course, we do not see them, for real particles are excitations. Higgs’ condensate has a very important consequence. The Higgs field and its condensation were proposed in the standard model of particle physics, as the mechanisms responsible for the finite masses of all known particles.

VI. FINAL CONSIDERATIONS

Several Nobel Prizes were awarded for research related to the concepts of boson associated with Bose-Einstein statistics. The latest of them was the 2013 Physics Nobel, awarded to a scientist for demonstrating advances in Bose-Einstein's condensate theory. Despite this, Bose himself was never honored with the Nobel Prize in Physics and never received the merits due. In the 2001 Nobel Prize winners, for example, the organizers mentioned that the discovery of Bose-Einstein condensation, a new state of matter, would bring revolutionary applications in fields such as precision, measurement and nanotechnology. It should have been mentioned that it was an experimental discovery, as this was a theoretical creation of Bose and Einstein, which was not even mentioned during the awards. The 1997 Nobel Prize in Physics was jointly awarded to Steven Chu, Claude Cohen-Tannoudji and William D. Phillips for the development of methods to cool and trap atoms with laser light for the purpose of studying the Bose Einstein condensate. In order to work better with atoms, it is also necessary to imprison them using a trap called the MOT (magneto-optical trap). It is usually composed of two coils with an inverted current direction where the magnetic field creates a restoring force resembling a conventional mass-spring system by confining the atoms in the center of the trap. Despite all this apparatus, we still cannot get the lowest temperature to get a BEC. For this, the aforementioned evaporative cooling is used. This is only achieved by disconnecting the lasers from the trap, causing the atoms to escape. If everything is done correctly, one gets what some call the 5th state of matter that is the Bose-Einstein condensate, one of the most fragile things there are. It is important to emphasize that in order to reach the condensate one does not pass through the liquid and solid states, but transits straight from the gaseous to the condensate.

REFERENCE

[1]. BOHN, J. Research about Bose Einstein Condensate, text available in http://jilawww.colorado.edu/www/press/bose-ein.html, access in 20/04/2018
[2]. ANDERSON, M. H., ENSHER, J. R., MATHEWS, M.R., WIEMAN, C. E. and CORNEL, E. A. Science 269, 198 (1995).
[3]. BAGNATO, V. S. Bose-Einstein Condensation, Revista Brasileira de Ensino de Física, vol. 19, no. 1, 1997
[4]. ENSHER, J. R. The First Experiments with Bose-Einstein Condensation of 87Rb. A thesis submitted to the University of Colorado in partial fullment of the requirements for the degree of Doctor of Philosophy, text available in https://jila.colorado.edu/sites/default/files/assets/files/publications/ensher_thesis.pdf.
[5]. BOSE, S. N., Z. Phys. 26, 178 (1924)
[6]. EINSTEIN A.,Sitz. Ber. Preuss. Akad. Wiss. (Berlin) 1, 3 (1925)
[7]. LANDAL, L.D., J. Phys. USSR 5, 71 (1941)
[8]. LANDAU, L. D., (1941). "Theory of the Superfluidity of Helium II". Physical Review 60: 356-358.
[9]. Oxford Experimental BEC Group. http://www-matterwave.physics.ox.ac.uk/bec/bec.html

Levada "What Is Bose-Einstein Condensate? "The International Journal of Engineering and Science (IJES),), 7.10 (2018): 45-49