Bose-Eistein Condesation Essay, Research Paper

Everything in the world around us is made up of particles. These particles can be placed into two categories called bosons and fermions. Bosons are particles that have integer spin values, such as 1, 2, 3 and so on.3 Examples of bosons are photons, which are quantum of electromagnetic radiation, phonons, which are quantum of vibrational energy, and most atoms. Fermions on the other hand are particles that have half-integer spin values, such as 1/2, 3/2, 5/2 and so on.3 Fermions are the most common particles, such as electrons, protons, neutrons, and even a few atoms. Since fermions form the elementary building blocks, fermions also make up individual atoms. When you put an even number of fermions together, what results is a composite particle with an integer spin number, or a boson. The significance of the spin numbers is that bosons tend to be uniform and in the same state. An example of this are the photons of a laser beam in the same energy state traveling in the same direction. In opposition to this, fermions are characteristically different. That is why electrons around an atom cannot have the same spin, hence the Pauli exclusion principle. This observation of the nature of bosons prompted Satyendra Nath Bose to develop some rules about photons, such as black body radiation. Einstein picked up this work by Bose later on, and suggested that some of the rules could be applied to other bosonic particles.4 Einstein ended up deriving a concept known as the Bose-Einstein distribution. He showed that if a sample of atoms were brought to a low enough temperature, that a large proportion would end up in the lowest possible energy state. Physically, the individuality of the atoms would disappear. The characteristics of the individual atoms, such as position and velocity would basically merge and become indistinguishable from each other. Having this large number of particles just sitting in the lowest available energy state is the formation of the Bose-Einstein condensate. It is this formation that causes a spike in the energy distribution of these atoms, right next to the origin in the figure below.3 Atoms have wave nature so they also have wavelengths, just as do photons, which is known as the de Broglie wavelength.3 The exact position of the atom cannot be known at low temperatures, only that it is in a general spot, known as a wave packet. This is the certain region in which the atom is expected to be found.4 As the temperature of the atoms is lowered further, the de Broglie wavelength increases and the size of the wave packet increases.2 The individual atoms can still be differentiated, but when the temperature reaches a low enough value, these wave packets overlap with neighboring wave packets. It is when the de Broglie wavelength of one atom overlaps one of another that the Bose-Einstein condensation occurs.5 This phenomenon results in a single macroscopic wave packet, composed of many individual wave packets, which behave as if they were a single atom.2 It took over 70 years for Bose-Einstein condensation to go from theoretical predictions, to actually succeeding in creating a Bose-Einstein condensate. It was not until the June of 1995 that Eric Cornell, Carl Wieman, Michael Anderson, and their colleagues were able to accomplish this historical deed.5 One of the main reasons that it took so long for this to occur was that the lack of refrigeration technology prevented even entertaining of such thoughts. It was in the 1970 s when technology had advanced enough for researchers to attain temperatures that were cool enough, but yet another obstacle surfaced. For Bose-Einstein condensation to occur, the gas needs to be cooled far past the point where the atoms would normally freeze into a solid. This caused some problems because a solid cannot form a Bose-Einstein condensate.3 For Bose-Einstein condensation to form, the gas needs to reach a metastable state. The trick in doing this is to make sure that the system is clear of impurities, such as dust, and to keep the gas at low densities. If there is nothing for the crystals or droplets to nucleate onto, gas can be cooled below the temperature that it liquefies and becomes solid. The low densities are needed because it lowers the chance of three-body collisions, which can cause molecules to form. When two atoms collide, they will not form a molecule, because there is nothing to cause them to stick. But, if three atoms come together, the third atom can take the energy of the collision, leaving the two atoms stuck together as a molecule. If this occurs, more molecules can accumulate to form snowflakes.3 Having to use low densities also results in some additional problems. To get a Bose-Einstein condensate, low temperature and high densities are needed.5 The difficulty in having lower densities is that it causes a need for even lower temperatures. But since having the lower densities is a necessity, cooling techniques had to be devised to reach the temperatures needed. Laser cooling was one such technique that was developed. The main function of lasers is usually thought of as something to heat or burn with. That is true, but laser beams also carry momentum. The force from this light is exceedingly small, but when compared to say the mass of an atom, it turns out to be significant. Temperature is related to the energy of the atoms, which is related to their movement. So by slowing the atoms down, the temperature can be lowered. This is in effect how laser cooling works.4 Atoms have a resonant frequency at which they will scatter photons. Opposing tuned frequency lasers are then placed around the atoms. The lasers are tuned just below the resonant frequency of the atoms. This is to utilize the Doppler shift that occurs. The beam that is opposing the atom s path of travel will be shifted to a higher frequency, so that the atom will be affected by those photons, and slow. The laser beam in the direction of the atom s path of travel will not push the atom, because it s frequency will be shifted lower away from the resonant frequency of the atom. So, no matter which direction the atom is traveling, it will be slowed, lowering the temperature of the gas. The atoms cannot be cooled past a certain point, because of the random jostling the atoms undergo from the collisions with photons. This is the first step in reaching the extremely low temperatures needed for Bose-Einstein condensation. The use of the lasers also gives the added benefit of trapping the atoms where they intersect, keeping the atoms away from the much warmer walls of the cell, or container.3 Since temperature describes the average energy of the atoms, by removing the especially energetic atoms, the average energy will decrease as will the temperature. This technique called evaporative cooling is how the gas is cooled even further. Each atom has a magnetic moment that interacts with a magnetic field.6 Taking advantage of this characteristic, atoms can be trapped in a magnetic field. By arranging the magnetic fields in the shape of a bowl, with a local minimum in the center, atoms with magnetic moments parallel to the magnetic field will be attracted to the center.5 The temperature is lowered by decreasing the strength of the magnetic field. This is like lowering the sides of a bowl. As the atoms move around and collide with each other in this magnetic trap, the more energetic atoms escape from the trap, leaving the atoms that have less energy to collect in the center of the trap.3

One way to think about this is to take for example, a hot drink. It is basically a container of atoms with different energies. Well, leaving a hot drink out in the open will result in a cool drink. This happens, because the higher energy atoms will leave the hot drink as steam, leaving only cooled drink. The temperature is lowered by loss of some of the drink. This is the same principle that is used with the magnetic trap. As the atoms cool, the density increases. This is due to the fact that the atoms do not have energy to move up the sides of the walls, and so begin to settle in the bottom of the trap. So, the density is increased in addition to the temperature being lowered, which are help the conditions for the formation of the Bose-Einstein condensate.4 Because of the weak interactions between atoms, evaporative cooling becomes a bit ineffective at the low temperatures involved.5 That is why another procedure is done in conjunction with evaporative cooling. An energetic atom might move up the wall of the trap, but not high enough to be expelled because of the attraction to the minimum of the trap. The process that then takes place is the application of a radio-frequency oscillating magnetic field to the area of the magnetic trap that contains these higher energy atoms.1 The radio-frequency magnetic field works by changing or flipping the spin state of the atom.6 The atoms that were being attracted by the magnetic trap, are now repelled, and fall out of the bowl. By adjusting the frequency of the radio-frequency magnetic field, the effective lip of the bowl will move inward toward the center, increasing the chance that the hotter atoms will leave.3 As the frequency of the radio-frequency magnetic field is slowly decreased, evaporation is induced deeper in the cloud of gas. This lowers the temperature of the gas even further and also increases the density slowly. When a certain point is reached, the density suddenly jumps, which is the start of the Bose-Einstein condensate. A thermal cloud forms, which is round and smooth.3 As this cloud is cooled even further, it begins to shrink and a spike appears in the middle of it.4 This is the appearance of the Bose-Einstein condensate. By cooling it even further, the Bose-Einstein condensation can be isolated by the loss of the normal atoms. Initially, hydrogen was thought to be the gas that would be the easiest to form a Bose-Einstein condensate. Theorists predicted this because hydrogen resisted the atom clumping that comes right before freezing, and with it having the longest wavelength due to its light weight, would allow the Bose-Einstein condensation to occur at a higher temperature.5 It turned out that hydrogen was not the best candidate for Bose-Einstein condensation. This was because of the difficulty involved in manipulating the atoms because of the larger energy level spacing in hydrogen. So, other atoms were tried in the attempt to form a Bose-Einstein condensate. Alkali atoms were the first to be used to form the Bose condensate. This was due to the fact that the larger atoms collide at higher rates, so that the energy is shared more quickly, which allows the condensate to form before clumping occurs.4 With the success of research groups in forming the Bose-Einstein condensates in the alkali atoms, interest was again raised in hydrogen. Thomas Greytak and Daniel Kleppner led a group of researchers in a quest to form the condensate in hydrogen. It took them over 20 years, but on June 12, 1998 they were successful.1 They had made slight modifications in the cooling techniques, and with these small improvements, were able to finally reach their goal. This achievement is very significant in what it leads to. These developments bring a new field of matter wave physics.2 Bose-Einstein condensation is intriguing in that is offers a macroscopic view of the quantum world. Usually, quantum mechanics can not be observed, because of the random nature of many particles interacting with each other. But when a Bose-Einstein condensation is formed, the characteristics of each atom are the same for all the others. The shared waveform extends across the entire sample, and can be observed without destroying it.2 What is so significant about hydrogen is that because of all the equations that have been derived for hydrogen and since its atoms interact very weakly with each other, that first principal calculations can be made. This was also another reason that the formation of the Bose-Einstein condensation in hydrogen was so difficult. In its spin-polarized state, it is also the best approximation to an ideal gas.5 To analyze the condensate, it has to be detected first. In the experiment that was carried out with alkali atoms, the Bose-Einstein condensation was imaged by use of a resonance tuned laser beam. The beam was passed through the atomic cloud, and imaged onto a charged couple array.3 As the photons enter the atomic cloud, they are scattered in all directions. This causes shadows to form in the image that the beam casts on the array. The darkest areas on the charged couple array correspond to the areas of greatest density of the atomic cloud, which would be the Bose-Einstein condensate. But, before all this can take place, the cloud needs to be made larger for imaging to take place. The magnetic field is turned off and the atoms are allowed to come apart. A laser pulse then images the cloud. From this image, the velocities of the atoms can be determined, which also gives the temperature.4 For the group of researchers that formed the condensate in hydrogen, visual imaging was not possible because of the shortness of the wavelengths that hydrogen radiates. The technique that is they use it two photon spectroscopy. This technique entails the excitation of the atoms to a higher state. By use of a laser beam, the atoms are detected by how much they detune the photons of the laser. As the laser hits the atomic cloud, the photons undergo a Doppler shift depending on the direction of travel of the atom. The frequency is dependent on the density of the atoms, and so a small peak forms as the condensate is detected.5 In addition to the developing theories about condensates, researchers are also pondering practical applications for Bose-Einstein condensation. Last year in fact, an atom laser from a sodium Bose-Einstein condensation was constructed. As research continues, new physic are being developed.

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