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SUPERFLUIDITY*

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Preface

This article is about "Superfluidity". We are all familiar with fluids, the commonest of which — water – is an integral part of our daily lives. Water does not stand still, it flows from place to place like a stream. However, in the acronym "Super" we discern a distinct allusion to the fluidity of water, which is quite different from the natural form of water.

Since this year marks the centenary of the birth of Bose Statistics, it is our endeavor to link superfluidity with Satyendranath Bose's work. The inception of the latter can be traced to the famous letter that Bose wrote in 1924 from Dhaka University to the renowned German physicist Albert Einstein. Along with the Bose statistics (often called the Bose-Einstein statistics) was born another epithet: "boson", thanks to the English physicist Paul Dirac. All the elementary particles in this Universe are categorized as either bosons or fermions; the latter obey Fermi-Dirac statistics. While bosons have their intrinsic angular momentum called, 'spin', as integer multiples of the Planck constant $\hbar$, the fermions are endowed with spin which are half-integer multiples of $\hbar$. As our principal focus is Bose's monumental contribution, we explore in this article the relation of the boson to superfluidity.

It is pertinent to recall here that the letter that Bose scribbled to Einstein was based on Planck's analysis of the black body radiation and the associated "light quantum". It must be stressed here that although the light quantum is a boson with an intrinsic spin of $1\hbar$, it possesses a zero mass and as a consequence, it moves with the speed of light. This is yet another discovery of Einstein in 1905. The motion of light does not slow down or accelerate unlike elementary atoms such as helium (He) that exhibit superfluidity. Hence, superfluidity has no direct linkage with black body radiation *albeit* superfluidity arises from the Bose statistics and that is indeed the emphasis of our present discussion.

Bose Statistics and Bose Condensation

A basic entity in motion has two attributes – position and momentum. When it comes to Bose statistics the discussion is simpler when there are no attractive or repulsive forces between the entities, such as in the case of light quanta. In that case the momentum is adequate to specify the 'state'; there is no need for a separate mention of the position. The energy is also determined by the momentum. But, for a light quantum, the energy is further fixed by its frequency (or wavelength). It is the Trinity: energy-momentum-frequency, which is at the heart of the theory of Planck (1900) and Einstein (1905) in explaining the black body radiation.

Satyendra Nath Bose took the issue to a deeper level of the microworld. He asked, how many light particles can occupy the same momentum state? That this number can be infinitely large is his great discovery. Therefore, as the (average) momentum of the particles (read: bosons) decreases as the temperature is lowered, they also coalesce in number to the low momentum states. The point is, if the total number N is infinitely large, the number of particles with near-zero average momentum will also be exceedingly large. The temperature at which this change takes place is called a 'critical temperature'. At this temperature a 'phase transition' takes place. When the temperature goes down to absolute zero, all the particles would occupy the zero-momentum state – that is the key

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to condensation. The change of water to vapor (gas) is also a phase transformation, but the nature of Bose condensation is essentially rooted in quantum mechanics.

Helium

The great philosopher-poet Rabindranath Tagore was very close to Satyendranath Bose whom he dedicated his book in Bengali on science: *Viswaparichay* (1934 – 1937). Tagore wrote and we translate (selectively): *Helium is the gas that is just above hydrogen in weight. This gas is new to science – it was first detected during the solar eclipse of 1868. From inside the gaseous envelope of the sun came an indication of this unknown element. Finally, after thirty years, the famous chemist William Ramsay found a very small amount of this gas in the atmosphere of the earth. Following that, it was discovered in certain oil wells in North America. Because helium is very light it was extensively used to power spaceships. Since helium is not combustible like hydrogen it makes flying safe. It also finds applications in medicines.* Since the impact of Bose's work is the central theme of our piece, it is contextual to mention that it is his initiative that led Shyamadas Chatterjee to explore extraction of helium from the hot springs of Bakreshwar.

The above discussion pertains to helium in the gaseous form. But, just as water turns from vapor to liquid when cooled, helium also converts into liquid as the temperature decreases. Super-cold helium, at extremely low temperatures, finds enormous applications to technology, such as Cryogenics. A notable present-day example is in Magnetic Resonance Imaging (MRI). On the other hand, our objective here is to view helium in the light of the Bose statistics. In 1938, Russian physicist P. L. Kapitza and two Canadian physicists J. F. Allen and A. D. Misner showed that there is no viscous damping in liquid helium below – 270. 98 degree Celsius. The latter is really an ultracold temperature if we remember that water freezes into ice at O degree Celsius! Now, it is well in order to point out that when there is no viscosity a fluid can travel unimpeded or flow through a tube – it becomes a superfluid. Why is this phenomenon not seen in other neutral atoms such as neon? Well, neon solidifies well before it reaches the superfluid state. Thus, helium is exceptional to superfluidity – a great triumph of quantum theory and the Bose statistics.

Why is Helium a Boson?

The helium that we are talking about here has two protons and two neutrons inside its nucleus. Again, the helium atom is electrically neutral because the charge of the two electrons in the outer orbits compensates the charge of the two protons. As it turns out, the intrinsic spins of these six fermions cancel each other to reduce the neutral helium atom to a state of zero spin-angular momentum – hence, it is a boson. Therefore, the superfluidity of helium and its condensation is a direct consequence of the Bose statistics. The underlying phase transformation is called a 'Lambda transition', as the specific heat at the aforementioned critical temperature takes the form of the Greek letter: Lambda. The question may arise – what is the difference between this phase transformation and the Bose condensation of light quanta that we introduced earlier? The answer is: the light quantum has no attraction or repulsion, helium does! ❒