"Bose - Einstein Statistics"

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Fifty years ago a young Indian scientist put down on paper certain fundamental observations that he had made on the nature of light radiation. This brief paper of less than four pages, published in a German translation in Zeitschrift für Physik, Band 27 (1924), created a synthesis of two divergent pictures that we have had of light, and laid the foundations of the subsequent development of the quantum field theory of elementary particles. The nation is celebrating the Golden Jubilee of this fundamental discovery this year. The Prime Minister has set up a National Committee with herself as patron, the Minister of Science and Technology as Chairman, the Minister of Education as Vice-Chairman, and with many leading scientists as members.

Today (July 15) begins a two-week long scientific Symposium on Statistical Physics at the Indian Institute of Science at Bangalore with many of India's brightest scientists participating along with leading representative scientists from three other continents.

Let me avail myself of this opportunity to outline Bose-Einstein Statistics. At the beginning of this century Max Planck resolved a long-standing physical problem on the nature of radiation contained inside an enclosed cavity which is heated to some suitable temperature. Scientists had known that a study of this question required picturing the radiation as consisting of the excitations of a number of standing wave modes of the radiation. But the usually accepted principles led to not only incorrect, but nonsensical answers. Planck resolved this impasse by the simple but revolutionary quantum hypothesis: that the excitation of these modes could not be by arbitrary amounts, but only in multiples of a fundamental unit for each mode. With the quantum hypothesis Planck deduced the energy distribution inside a cavity, the so-called Planck distribution of "blackbody radiation", and thus initiated the quantum revolution. The profile of the father of quantum theory adorned the two-mark coin of Germany until recently.

Within four years Einstein showed that light beams which were pictured as continuous wave excitations exhibited particle properties in their interaction with matter in the photoelectric effect. Light incident on a clean metal surface ejected electrons out of it. The energy of the ejected electrons could be understood only if the light beam consisted of particles, later called photons. Many

years later Compton showed that the scattering of light by free electrons can be understood only by picturing collisions between electrons and particles of light, the photons.

Bose concerned himself with reconciling these two pictures. If we pictured the cavity as having excitations of the waves, we derive Planck's distribution law in agreement with experience. But should we not be able to derive it by picturing the radiation as consisting of a photon gas? The earlier attempts in this direction could not give the Planck law. The young Bose then boldly proposed that the statistical mechanics of a photon gas was not correctly given by the orthodox rules. We had to treat the photons in the photon gas as indistinguishable and strictly identical. This suggests a new rule for "counting particles". This new rule leads to different statistical behaviour of assemblies of photons and hence of the thermodynamics of the photon gas from what was obtained from the usual counting (called Boltzmann statistics).

Let me say a few words about statistical thermodynamics. To calculate the properties like energy density and specific heat of an extended system, we think of the system existing in many levels at the same time, each of the states constituting a petal of the lotus of the thermodynamic system, a veritable víśvarūpa. In taking such a surrealistic entity as this "ensemble" as a model for the thermodynamic system we are following time-honoured principles laid down long ago and tested in numerous physical applications. We must, in doing this calculation, decide how many possible states are there for the system and how much they are to contribute. The latter factor is known from general principles but Bose found that the former had been incorrectly calculated by Boltzmann seventy years before him and by all scientists afterwards. This led to many inconsistencies like the Gibbs paradox. The crux of the matter is that people did not recognize that strictly identical particles are really indistinguishable! If particle 1 is to my left and particle 2 is to my right and if the particles are strictly identical, I could not distinguish the situation if particles 1 and 2 were interchanged. In fact, we have only one condition. This should be contrasted with the case in which the particles are distinguishable, say by painting them different colors. In that case these two represent two different conditions. Bose proposed that the way we must choose to "count" states is to consider them as absolutely indistinguishable. He pointed out that if we do so, and only if we do so, we

may consider the many photon states to be the same as states of the electromagnetic field. The two pictures, one of a photon gas, and the other of a quantum electromagnetic field may be identified. With this synthesis he was able to show that we could obtain for the photon gas the same results as for Planck's quantum field.

This new picture has immediate consequences. The relative probability of two photons of the same kind is increased over what it would have been if photons were identical but distinguishable particles. We have thus a positive correlation between photons: photons tend to bunch together. This photon bunching is experimentally seen in photocount distributions and in the correlation of intensities leading to the Hanbury-Brown - Twiss effect. It is as if the photons attracted each other.

Albert Einstein was greatly inspired by Satyen Bose's work and saw that, rather than it being applicable only to photons, by some simple technical modifications it could be adapted to deal with more general gases. The two modifications dealt with particles which are permanent (unlike the ephemeral photon) and with particles of finite mass like helium atoms or heavy hydrogen again in contrast to the mass-less photon. With these modifications we could work out the statistical mechanics of Bose gases. This modification by Einstein of Bose's work has led us to call the new counting law Bose-Einstein Statistics. It leads to many novel effects like the condensation of the particles into a single large-scale quantum state at sufficiently low temperatures leading to a "superfluid" - a novel kind of fluid with no viscosity which does prodigious things. In its turn, this possibility has, in the hands of other scientists, yielded a clue to the theory of superconductivity.

The synthesis of the notion of a collection of photons obeying Bose statistics and the notion of the states of the quantum electromagnetic field laid the foundations of the quantum theory of fields. It developed, in the hands of Heisenberg and Pauli and of Dirac into the formulation of quantum electrodynamics. A technical simplification was made by Fermi but the complete formulation awaited the masterly work of Gupta involving as it does the use of a generalized space of states. In all these developments as well as in the subsequent theories of other fields and other species of particles the central idea has been the identification of the many-quanta states with the states of excitation of the field.

It has subsequently been found that while Bose's proposal that to do quantum physics correctly we must treat the particles as absolutely identical is universally valid, the scheme of Bose-Einstein statistics is not universally applicable. The periodic system of the chemical elements, atomic spectra, and properties of matter in bulk all had shown that electrons must obey the "exclusion principle", a rule which forbids that any two electrons can be in the same state of motion and spin. For these cases we must use a different rule for counting which takes into account this exclusion rule. This counting rule is called Fermi-Dirac (or Fermi) statistics. Electrons, neutrons and protons are seen to obey this scheme. On the other hand, pions and other pseudoscalar or vector mesons are seen to obey Bose statistics. In recent years we have begun to understand the basis on which this dichotomy is established. Particles whose spins (intrinsic angular momenta in units of Planck's constant divided by 2π) are integral, obey Bose statistics while particle species with half integral spins obey Fermi statistics.

The point of view concerning photons and consequently about other particles, that lies at the foundation of Bose statistics, sheds new light (no pun intended!) on the nature of a quantum particle. Since the various many-particle states are all states of the same underlying physical system, the addition or deletion of a particle is just a change of the dynamical configuration of that which is permanent, namely the field. But the field is just the embodiment of changes in space. The particles thus appear as simply the modifications of space, the modern paraphrase of the āptavākya : śabdagunamākāśaṁ.

The study of light has fascinated us Indians from the beginning of time. There is the celebrated discourse between Yajñāvalkya and Janaka on the nature of light and seeing in the Chandogya Upaniṣad. Even in our own times Sir Rāman found enchantment and enlightenment in light, colour and vision. It is perhaps essential that we look at nature around us in a one-pointed undistracted fashion to see: to see as a seer sees. This is essential science, in the ancient tradition of Viśvāmitra and the modern one of Bose and Rāman. And it is to be hoped that amongst us are thirty-year olds with such blessed recklessness as the young Bose who are quietly initiating scientific revolutions.