1995 Nobel Laureates in Physics

Frederick Reines Martin L Perl

Data gathered over the years support the view that the earlier e-μ universality, i.e. the similarity in the properties of the e and μ, can be extended to e-μ–τ universality. The earlier enigma regarding the existence of muon is thus deepened. It now becomes the so-called 'generation puzzle': among the ultimate constituents of matter, why do members of one generation behave exactly in the same way, except for the mass, as the corresponding members of another generation?

As for the tau mass, recent measurements at the Beijing Electron Positron Collider (BEPC) in China, give $m_\tau = 1777$ MeV, with an error which is less than 1 MeV. The relatively large mass of tau implies that many final states are accessible for the tau decay. The availability of several possible channels for decay makes the tau a very shortlived particle. Its mean life is presently known to be about

$$\tau_\tau = 3 \times 10^{-13}\ \mathrm{s},$$

with 1% accuracy, to be compared with

$$\tau_\mu = 2.197 \times 10^{-06}\ \mathrm{s}.$$

Suggested Reading

C L Cowan Jr. , F Reines, F B Harrison, J W Kruse, A D McGuire. *Science*, 124:103-104. 1956.

F Reines, and C L Cowan Jr. *Physics Today*, 10:12-18. August 1957.

M Goldhaber, L Grodzins and A W Sunyar. *Phys. Rev.* 105:1015-1017. 1958.

M L Perl, et al. *Phys. Rev. Lett.* 35: 1489-1492. 1975.

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Bose-Einstein Condensation Observed

High-Tech Experiment Confirms Long-Standing Prediction

Rajaram Nityananda

Statistics is concerned with the laws which govern large collections of random events. Statistical ideas entered physics through the work by Maxwell and Boltzmann on the kinetic theory of gases, more than a century ago. For example, they predicted that the probability distribution of one component of the velocity would be the bell shaped curve in *Figure 1. Figures 1 a,b* shows how the spread in velocity, (or momentum) of particles, decreases as the temperature is lowered.

In 1924, Satyendra Nath Bose, then in Dacca University, discovered a new form of statistics, which applies to indistinguishable particles.

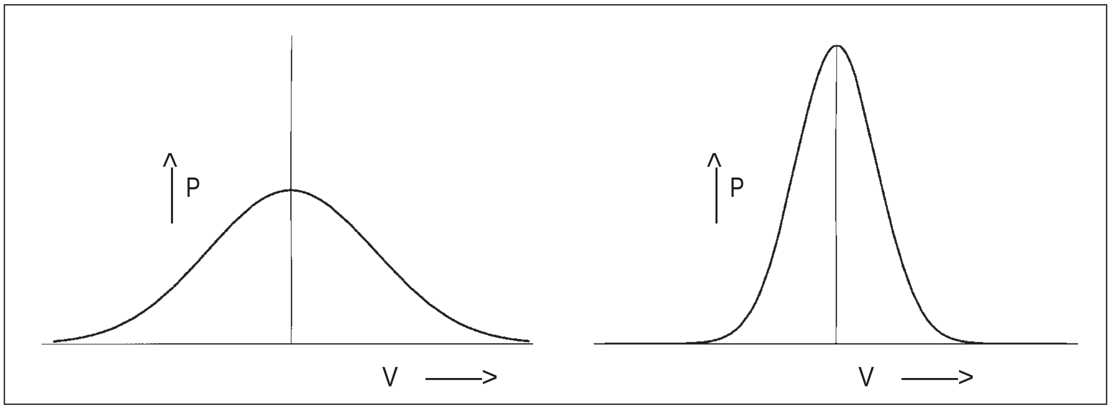
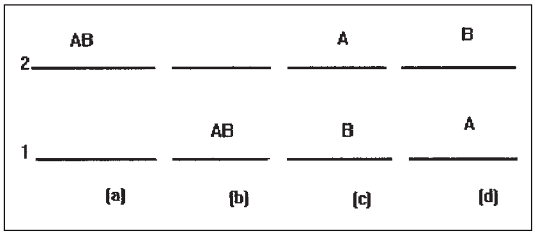


***Figure 1** Probability distribution P(v) for molecules to have a velocity V along a given direction. (a) at a higher temperature (b) at a lower temperature. The graphs show the Maxwell-Boltzmann distribution.*

To appreciate the new feature of his statistics, consider a situation in which two particles A and B are to be placed in either of two distinct *quantum* states 1 and 2. Boltzmann statistics recognizes four possibilities, which are shown in *Figures 2 a to d.*

According to Bose, the last two possibilities, (c) and (d), should be counted only as one, because the particles are indistinguishable. Notice that this modification increases the probability of the two cases (a) and (b), in which two particles occupy the same state, in comparison to the case where they occupy different states. Bosons — particles obeying Bose statistics — are thus said to exhibit *bunching* or a *preference for being in the same state*. The concept of discrete states, which comes from quantum theory, is essential to this argument.

***Figure 2** Four possible ways (a) to (d) of distributing two distinguishable particles A&B between two quantum state 1 and 2. (c) & (d) are the same where A&B are indistinguishable.*



Bose's historic paper (see page 114) applied these ideas to the radiation emitted by a black body *i.e.*, photons. Einstein translated this paper into German for publication, hailed it as a great achievement, and took one more daring step forward. He applied the same counting rule to a gas like helium. His calculation showed that as the gas is cooled, the shape of the momentum distribution becomes more sharply peaked than the Boltzmann case (see *Figure 3a*). But even more important, below a special value of the temperature, a qualitatively new feature appears. A finite fraction of the total number of particles occupy the lowest energy state. This is shown as the spike in the probability distribution. (*Figure 3c*)

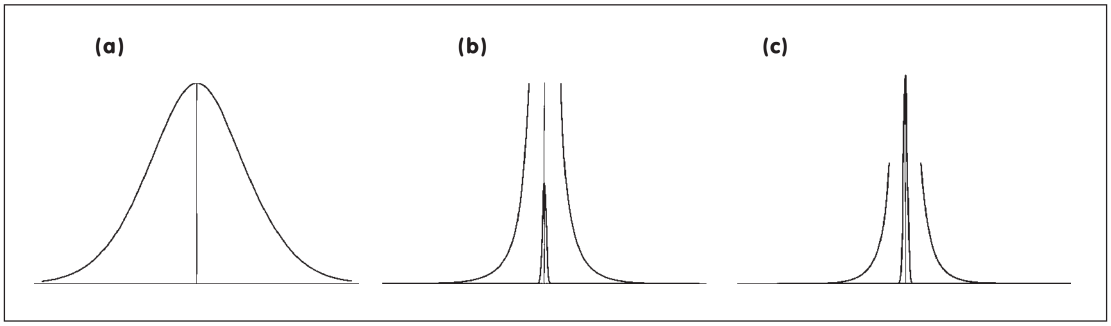
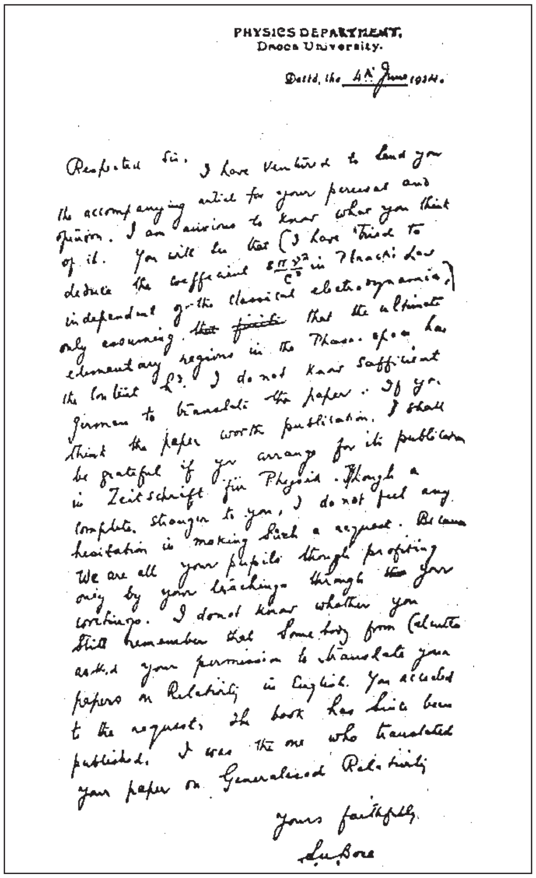


***Figure 3** Velocity probability distribution according to Bose-Einstein statistics, with temperature lowered as one goes from (a) to (b) to (c). Note the slight difference in the shape of the curve in (a) as compared to Fig 1a. At the lowest temperature (c), a fraction of the molecules condense into a 'spike' at zero momentum.*

This fraction increases as one goes to lower temperatures. It is important to note that this *condensation* is in momentum space, unlike the usual condensation of a gas to a liquid, which occurs in position space. The other important feature is that this condensation is purely because of quantum statistics. There need be no attractive force between the particles.

Liquid helium shows remarkable behaviour at low temperatures. It is strongly believed that this is due to occupation of the zero momentum state. But the picture is complicated by the strong forces between neighbouring atoms in the liquid. Thus, one could say that the original prediction of Bose-Einstein condensation was not experimentally realised. This situation has now changed with the recent experiments at Boulder, in the USA, by a team of scientists working with the vapour of rubidium, an alkali metal. The isotope of rubidium used has integer total angular momentum, like helium (for which it is zero) and hence obeys Bose statistics. The reference to the original paper is given at the end of this article.

The density of atoms in the Boulder experiment was only about 10^{12} per cubic centimetre — far lower by a factor of 10^{11} than in normal matter. Thus the separation of neighbouring atoms was about 10^{-4} cm. To get a significant probability of two atoms in the same quantum state, it is necessary for the de Broglie wavelength to become larger than this separation. This wavelength, characteristic of quantum behaviour, is inversely proportional to the momentum which should therefore be very small. Since the rubidium atom is quite massive, this requires a very low velocity — less than one centimetre per second! The corresponding temperature is about 170 nanokelvin (1.7×10^{-7} °K!). The two remarkable technical feats involved are (a) reducing the kinetic energy of the atoms to such a low value, (b) keeping the 2000 atoms confined to a space of size about 10^{-3}cm, without material walls (which would of course heat the atoms).



PHYSICS DEPARTMENT,
Dacca University.

Dated, the 4th June 1924.

Respected Sir, I have ventured to send you the accompanying article for your perusal and opinion. I am anxious to know what you think of it. You will see that I have tried to deduce the coefficient $\frac{8\pi\nu^2}{c^3}$ in Planck's Law independent of the classical electrodynamics, only assuming ~~that~~ ~~finite~~ that the ultimate elementary regions in the Phase-space has the content h^3. I do not know sufficient German to translate the paper. If you think the paper worth publication I shall be grateful if you arrange for its publication in Zeitschrift für Physik. Though a complete stranger to you, I do not feel any hesitation in making such a request. Because We are all your pupils though profiting only by your teachings through ~~the~~ your writings. I do not know whether you still remember that somebody from Calcutta asked your permission to translate your papers on Relativity in English. You acceded to the request. The book has since been published. I was the one who translated your paper on Generalised Relativity.

Yours faithfully,
S. N. Bose

The first stage of cooling is achieved with a set of laser beams, propagating in different directions. (This seems strange since we usually think of such beams as a source of heat!). Their frequencies are tuned to just below the natural (resonant) frequency of the atom. As an atom moves in any direction, the Doppler effect shifts the frequency of an oppositely directed beam upwards so that it has a greater probability of colliding with the atom and slowing it down. The next stage of cooling is by evaporation — as in the humble mud pot!. The trap for the atoms uses specially designed magnetic fields, as well as careful control of the magnetic moments of the atoms to keep them antiparallel to the field. Under these conditions, atoms are repelled from the strong field regions, which act as walls. The magnetic field is also used cleverly to control evaporation.

All these techniques were of course perfected by many researchers working for several years, before being used in the final demonstration of Bose-Einstein condensation. To measure the momenta of the particles, the trapping magnetic fields were reduced so that the atoms expanded freely, moving a distance proportional to their velocity. The spatial distribution of the atoms was measured by casting a shadow with (yet!) another laser beam. The measured momentum distribution showed the spike characteristic of the lowest energy state in the trap. Apart from being a striking illustration of basic physical principles, the condensation will undoubtedly find uses in precision measurements, and in exploring new regimes in the behaviour of interacting atoms at low temperatures. There is poetic justice in the use of lasers, which depend on the statistics proposed by Bose for radiation, to finally verify and demonstrate Einstein's brilliant extension of Bose's work to atoms.

Suggested Reading

W H Anderson, J R Ensher, M R Matthews, C E Wieman, and E A Cornell. *Science*. **269: 198 1995.**

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