Speech at the occasion of the NWO/Huygens Lecture 2000 by Carl Wieman

New levels of control at low temperature

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Introduction

It is this year exactly 100 years ago that Max Planck, much against his intuition, introduced the idea that the energy content of an electromagnetic field (light) cannot be changed in a continuous fashion but exclusively in discreet quantities, the quanta of light - presently known as photons. Planck came to this conclusion by analyzing the spectrum of the light emitted by a hot oven, when varying its temperature. We all are familiar with the change in color of a piece of coal from white-hot via red to black when it cools down. We also know it from the glow of incandescent lamps. In physics this behavior is known as black-body behavior. It is good to realize that by careful analysis of this familiar radiation behavior of a black body, Planck initiated a scientific revolution that has provided the foundation for many aspects of the prosperity that we currently experience in the industrialized world. In science, the explanation of the black body spectrum marked the start of the development of quantum physics.

It is a pleasure and honor that the organizers of the Huygens Lecture have selected a major recent discovery in quantum physics – the observation of Bose-Einstein condensation – as the topic for the lecture in this centennial year. It is also a pleasure that Carl Wieman as one of the prime movers behind this discovery has accepted to deliver this lecture. This year we also celebrate the 50th anniversary of the Netherlands Organization for Scientific Research (NWO). Organizations like NWO are – world wide – of vital importance for a healthy scientific climate. In the Netherlands, NWO has funded over the last half a century some of the finest scientific research and has enabled, in close collaboration with Dutch universities, the research education of a major fraction of the present Dutch scientific community. Therefore, I wish NWO a bright future to enable the continuation of research at the highest level and with attention to the proper balance between curiosity driven and prosperity generating aspects of modern science and technology.

It is often said that scientific discoveries raise more questions than are answered. The topic of today is no exception to this rule. Bose-Einstein condensation itself emerged in its earliest form as a proposed possible consequence of the quantum theory of light, which had proven so successful in explaining the radiation behavior of black bodies. Pushing the analogy between atoms and waves to a new extreme, Albert Einstein predicted in 1924/1925 the existence of an entirely new type of condensation phenomenon for a gas at very low temperatures and purely induced by quantum effects [1]. It took 70 years before Bose-Einstein condensation of gases could be demonstrated experimentally. This important result was obtained in the research group of Eric Cornell and Carl Wieman at the Joint Institute for Laboratory Astrophysics (JILA) in Boulder in the American state of Colorado [2]. The achievement of this scientific milestone triggered, aside from a lot of general interest in the scientific community and the public at large, many new questions and ideas that are currently actively explored in research groups all over the world [3].

NWO asked me to act as a co-referent at the occasion of the Huygens Lecture of Carl Wieman: *Bose-Einstein condensation, a new form of matter at a temperature near absolute zero*. In formulating my comments I will put emphasis on the scientific context in which the physics of Bose-Einstein condensates has played and plays such a marked role.

Bose-Einstein condensation – what took so long?

During the yearly national science week, you are welcome to spend a Sunday afternoon in Amsterdam Watergraafsmeer and visit the open house of the FOM-institute for Atomic and Molecular Physics (AMOLF). There, you can push a button to produce a Bose-Einstein condensate for yourself. After all it only takes half a minute to prepare one, starting from a gas cloud at room temperature. Hence, during one afternoon, we can serve many customers with a fresh sample! From this perspective it may be hard to understand the slow acceptance of the concept of Bose-Einstein condensation and the struggle for its experimental observation over many years. It may therefore be good to spend some time on the role of Bose-Einstein condensation in 20th century physics and insights that had to be developed to enable its observation. In the second half of my presentation I will enter into some new developments enabled by the availability of condensates.

In 1924 the young Indian physicist Satyendra Nath Bose attracted the interest of Einstein by presenting him with a novel derivation of the Planck radiation law in which the radiation field of the oven was constructed by exciting the oscillation modes in an optical resonator. The quantum gas of Einstein was a generalization of this idea [1]. The moving atoms in a gas are represented by matter waves in very specific modes of oscillation, in close analogy with the oscillation modes of the thermal radiation field in the optical resonator of Bose. The internal structure of the atoms, the subject of the atom model of Niels Bohr, is not considered in this model. In working out the analogy a major difference between the radiation field and the matter field had to be accounted for: the number of atoms in a gas is conserved, whereas such a restriction does not exist for the number of photons in a light field. This conservation of atom number turned out to have an unexpected consequence: cooling the quantum gas leads at a certain temperature to a phase transition in which the gas splits in two parts. One part was predicted to behave as a gas at the unattainable absolute zero of temperature, with the other part containing all thermal energy. This phenomenon is presently known as Bose-Einstein condensation (BEC). Although phase transitions are familiar in physics (just think of the condensation of water vapor into droplets of liquid on a cold window) the BEC transition is a very special one as it occurs also in the complete absence of interactions (repulsive or attractive) between the atoms. It is a pure consequence of the quantum mechanical description of the motion of the atoms.

The glowing oven studied theoretically by Planck was close to the experimental practice of the epoch. The quantum gas of Einstein was a highly abstract construction that could, in the absence of a practical example, not arouse much enthusiasm among his colleagues. As can be read in the Einstein biography by Abraham Pais also Einstein had a reluctance to discuss the subject and did not return to the topic in later years [4]. His early suggestion to look for BEC in the gas of electrons in metals proved rapidly untenable and the presence of interactions between the atoms in any realistic gas may well have been regarded as to overwhelm the delicate quantum features of the theory. It became clear that there are two types of quantum gases, the quantum gas of Einstein in which the gas particles show the same statistics as photons is know as the Bose gas. Quantum gases that behave like electrons are called Fermi gases.

The interest in Bose gases returned after Fritz Londen pointed to a possible relation between BEC and the famous "lambda transition" in liquid helium a 2.18 Kelvin [5]. Below this temperature the liquid shows friction-less flow and it was speculated that this could be related to the presence of a Bose-Einstein condensed fraction in the liquid. However, the dilute gas picture of Einstein simply could no explain the complex interactions in the dense liquid helium.

Remarkably, in spite of the accepted absence of even a single practical example, the hypothetical quantum gases became a key tool in the theoretical analysis of systems of many interacting particles (many-body theory). Some of the greatest theoreticians of the 20th century like Lev Landau and Nikolai Bogoliubov contributed to this subject. As a result the Bose gas has become part of the general physics curriculum at university level [6]. At research level, in the nineteen sixties the theoretical interest in the quantum gases declined in favor of theories capable of describing the experimentally available dense fluids like helium-3 and 4.

The action on Bose gases resumed at the experimental front in the nineteen seventies when it was realized that the conditions for BEC might be met in *metastable* systems, in particular spin-polarized atomic hydrogen. Theoretical analysis showed that by aligning the magnetic moments (spins) of the hydrogen atoms the inter-atomic interactions could be reduced to the level where the gas does not liquefy, even at the absolute zero of temperature. In November 1979 this was demonstrated experimentally at the University of Amsterdam [7]. Although this was a big advance, Bose-Einstein condensation in hydrogen turned out to be extremely difficult and was only realized in 1998 at MIT in the group of Tom Greytak and Daniel Kleppner [8]. In hydrogen it turned hard to maintain the spin-polarization. Moreover hydrogen atoms are difficult to handle experimentally and this made the experiments time consuming. Nevertheless many results, both experimental and theoretical, obtained with hydrogen have retained their value in the daily practice of experiments with Bose-Einstein condensates all over the world.

Interestingly, in 1995, BEC was first observed in small optically cooled gas clouds of the rubidium isotope 87 (^{87}Rb), which is – at first sight – even less stable than spin-polarized hydrogen because it normally forms a solid even at room temperature.

Bose-Einstein condensation – significance and future

As the experimental practice of experiments with ^{87}Rb were presented in the lecture by Carl Wieman, I will restrict myself here to some points which I regard as main assets of the scientific breakthrough obtained at JILA. (a) BEC was obtained with methods that can be applied to a large class of systems. This enables the custom design of new quantum systems by properly selecting the element of choice. Only a few years ago the only choice was the quantum fluid helium-4. Presently, even the production of molecular condensates is under discussion. Also Fermi gases are being investigated with these methods. (b) BEC was realized with methods that are readily accessible to many research groups. This enables a rapid development of the field and offers prospects for application. (c) BEC has brought together the scientific communities of low temperature physics and laser physics (quantum optics). This is presently resulting in a valuable "knowledge confrontation" that is generating new ideas for future research.

It is outside the scope of this comment to give an overview of the enormous scientific harvest that has been obtained over the last five years [see for instance ref. 3]. However, the results can be roughly classified in four groups.

(a) Experiments providing insight in the properties of Bose gases at low densities (a factor 10000 below the atmospheric density) and the effects of interactions between the gas atoms. The observation of the formation kinetics of a condensate is a prominent result from this class that cannot be obtained in any other system [9]. The recent observation of vortices reported by Wieman is another.

(b) Experiments using Bose-Einstein condensates to produce giant matter waves and to explore their analogy with light beams emerging from a laser. This work is known as the development of the "atom laser". In experiments of this type one can observe interference fringes between beams of atoms demonstrating the wave nature of the condensates [10, 11]. An example of such beams emerging from a condensate, obtained at AMOLF [12], is shown in figure 1. The magnetic trap used to prepare these samples is shown in figure 2. At present only pulsed atom lasers have been demonstrated, all generated by depletion of a Bose-Einstein condensate. The challenge is here to produce a continuous atom laser.

(c) A revival of the theoretical work on dilute Bose gases, picking up the work where it was left in the sixties in the absence of feedback from experiment and with fresh input from the quantum optics community [3].

(d) Application of Bose-Einstein condensates for precision measurements of gravity and frequency [13]. This direction has been a continuing source of innovation in physics. It may well be that Bose-Einstein condensates will prove most valuable to provide scientific advances in this particular direction.

Clearly the exploration of the quantum gases has a bright future, with many prominent results to come.

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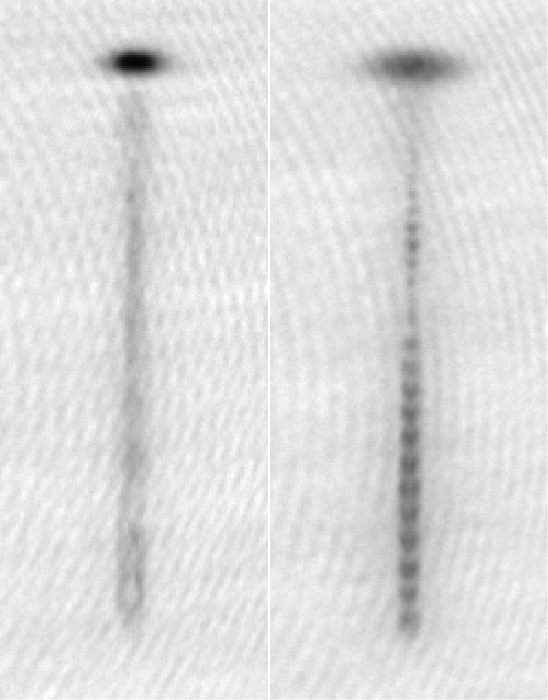

Figure 1. (a-left) Atomic beam (atom laser) coupled out of a Bose-Einstein condensate using a radio frequency magnetic field in combination with gravity. (b-right) two overlapping beams coupled from different parts of a condensate and showing interference.

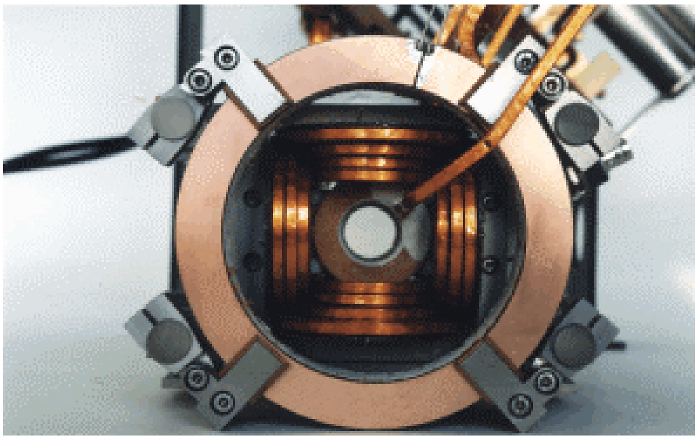

Figure 2. Magnetic trap used to confine Bose-Einstein condensed samples at the FOM institute AMOLF.