Bose-Einstein Condensation in a Dilute Atomic Vapor

An unavoidable consequence of quantum mechanics is that, for sufficiently short length scales, all objects appear to be "wavy." We do not notice this effect in our everyday lives because, for objects larger than an electron, the length scale over which the waviness occurs is fantastically short, far too small to be observed by the unaided eye. Nature makes an exception to this rule, however, in the case of extreme cold. As objects are cooled very close to absolute zero, their characteristic quantum-mechanical wavelengths become increasingly long. This tendency towards ever-expanding wavelength culminates in a dramatic phenomenon known as "Bose-Einstein Condensation" (BEC).

BEC was originally conceived in 1925 by Albert Einstein, who calculated that if a gas of atoms could be cooled below a transition temperature, it should suddenly condense into a remarkable state in which all the atoms have exactly the same location and energy—in modern language, the wave-function of each atom in a Bose-Einstein condensate should extend across the entire sample of gas. For a dilute gas, the requisite transition temperature is so low as to be unachievable by the technology of Einstein's day. By the 1980s and early 1990s, however, cooling techniques had advanced to the point where a number of experimental groups around the world felt emboldened to attempt to realize Einstein's original vision. Many of the necessary advances came from NBS/NIST atomic physics laboratories. The first successful creation of dilute-gas BEC, announced in the NIST publication *Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor* [1], was both a natural continuation of a 75-year tradition of NBS pre-eminence in spectroscopy (which is detailed in several other entries in this book [2-5]) and a striking confirmation that present-day NIST research is at the cutting edge of modern technology.

The scientific motivation to create and study BEC in a gas stemmed from the long-held belief that the mechanism underlying BEC is the same mechanism responsible for the mysterious effects of superconductivity and superfluidity. Indeed, in the broadest sense the electrical currents that flow (without resistance) in a superconducting metal and the liquid currents that persist (without viscosity) in superfluid helium are basically Bose condensates. But liquids and solids are much more complicated than the relatively simple gas-phase system that Einstein first envisioned, and it is not easy to connect the elegant mechanism that Einstein proposed with the complex behavior of solids and liquids. If one could create a Bose condensate in a gas, it was reasoned, one would have a well-characterized model system, a system that might illuminate the counter-intuitive behavior of its liquid and solid predecessors.

The technical motivation for creating a BEC was equally compelling. Much of the standards and metrology work that NIST is charged with performing relies on precise spectroscopy of various internal resonances in atoms. When it comes to spectroscopy, the general rule of thumb is "colder equals more accurate." Colder atoms move more slowly, which means they can be probed longer, with correspondingly narrower resonance lines. In addition, systematic errors are often more easily controlled at lower temperatures. For a gas of atoms, the natural and obvious limit of improved cooling is exactly the Bose-condensed state. Thus from both technological and scientific viewpoints, there were compelling reasons to push the techniques of refrigeration to the ultimate limits with the goal of creating BEC.

The first condensates were formed at NIST at temperatures well under a microkelvin. To reach these unprecedented temperatures required a two-stage cooling technique. The first stage of refrigeration is provided by laser cooling. Of the three or four most prominent players in the development of laser cooling, two (David Wineland and Bill Phillips) are long-standing Bureau scientists; two of their most influential papers are described in this volume [6,7]. As powerful as laser cooling is, it is not sufficient on its own to reach BEC temperatures. The second stage of cooling is known as evaporative cooling. The laser-cooled atoms are collected in a magnetic trap (another NIST development [8]) which provides near-perfect thermal isolation from the surrounding environment. Via a technique known as rf evaporation [9], the trapped atoms with the most energy are ejected from the magnetic trap. The remaining atoms have, on average, less energy per atom, and are therefore colder. After evaporation has cooled the atoms to a temperature perhaps another factor of a hundred colder than the laser-cooled sample, the condensate begins to form.

The presence of condensates was originally detected by velocity-distribution information observed in time-of-flight images. The magnetic fields used to confine the atoms were very suddenly turned off. The residual thermal and quantum energy of the atoms caused them to fly apart. After a brief delay, the atoms were illuminated with a strobed flash of laser light, and their image was captured on an electronic screen. The atoms with large thermal velocities in the trapped cloud ended up far from the center of the image; atoms with relatively low velocities did not travel as far during the delay time and contributed to the central portion of the recorded density. Fig. 1 shows a series of three such images; from left to right they correspond to images taken of three clouds at progressively lower temperatures [10]. In the left-most image, the atoms are not yet condensed; the distribution of velocities is well approximated by a conventional Maxwell-Boltzmann thermal distribution. In the center image, the condensate has begun to form; the central spire corresponds to the near-stationary atoms of the condensate. The final, right-most cloud is a near-pure condensate. The central feature amounts to a photographic image of a single, macroscopically-occupied quantum wavefunction.

The original observation of BEC in a gas of atoms occurred in June of 1995. A few months earlier, several groups (most notably the NIST/CU collaboration in Boulder, and groups at Rice University and at MIT) were very close to achieving Bose-Einstein condensation. All three groups presented their progress in invited talks at the May 1995 meeting of the American Physical Society. The audience was left with the impression that the long-standing goal of BEC might be realized quite soon. There was a pronounced sense of keen, but good-spirited, competition that added to the general anticipation felt in the physics community.

Ultimately, the NIST group prevailed and its paper [1] appeared, as the cover article, in *Science* magazine on July 14th, 1995. In the same issue, *Science* also ran a "perspective" piece by Keith Burnett, of Oxford University, in which he referred to the achievement of Bose-Einstein condensation as a sort of "Holy Grail" of physics. The announcement of Bose-Einstein condensation attracted an unusual amount of attention from the lay public. There were front-page articles in the *Washington Post,* the *New York Times* and the *Los Angeles Times,* and even professional entertainers made remarks about scientists creating new states of matter. The scientific press was also duly impressed: the work was written up in all the major science magazines; the paper won the AAAS Newcomb-Cleveland award; and in December 1995 *Science* deemed BEC the "Breakthrough of the Year."

In the years immediately following NIST's breakthrough result, there was an enormous surge of interest in the field of BEC. Within a few months, the group at MIT had successfully created a sample of BEC over a hundred times larger than the initial NIST result [11]. Theoretical calculations performed at NIST predicted that the condensate clouds should support standing-wave acoustic modes [12], with resonance frequencies determined by solutions to a macroscopic quantum wave equation. Within a year, these predictions were

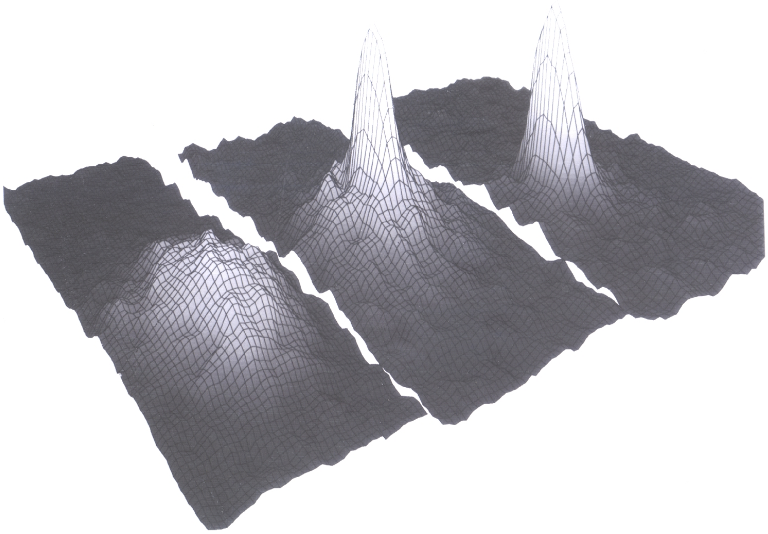

Fig. 1. A series of images of progressively colder clouds of rubidium gas. In the center image, a Bose-Einstein condensation can be seen emerging from the background thermal gas. A color version of this image was featured on the 1996 calendar distributed by the American Physical Society.

experimentally verified by the original NIST group in Boulder [13] and also by the group at MIT [14].

The field of BEC research continues to expand. Around the world, many experimental groups are now capable of producing the substance. For a recent review, see reference [15]. Hundreds of theoretical papers on BEC are published every year. The major atomic physics and low-temperature conferences all have multiple sessions devoted to BEC, and every year a number of specialty workshops are held on the topic around the world. The original experimental paper [1] has now been cited in the scientific literature more than 1000 times, and citations continue to accrue at a rate of more than 200 per year.

The first major application of BEC has been to make possible the development of "atom lasers," intense beams of coherent atoms which are very analogous to the more conventional "photon lasers" of light. BEC is the starting point for this rapidly evolving technology—after atoms are cooled into a BEC, they are ejected out of the trap in a highly collimated, monoenergetic beam [16, 17].

The longer-term technological and economic significance of BEC and the "atom laser" will never rival that of the optical laser. The ability to create coherent-like beams of atoms will likely find specialized applications, however, in certain high-technology fields: BEC will enhance the capability of very-high-precision, atom-interferometric metrology. On a more speculative note, one could imagine coherent-source atomic lithography being used in certain nanofabrication situations.

Eric Cornell's graduate work was on precision mass spectroscopy; he received his Ph.D. from MIT in 1990. He began trying to reach Bose-Einstein condensation in the same year. Since 1992 he has been a staff physicist in NIST's Quantum Physics Division. He is a Fellow of JILA and Professor Adjoint in the University of Colorado Physics Dept. His work in Bose-Einstein Condensation has been recognized by many prizes and awards, including NIST's Samuel Wesley Stratton Award, the Department of Commerce Gold Medal, the Fritz London Prize in Low Temperature Physics, the King Faisal International Prize in Physics, the Lorentz Medal (Royal Netherlands Academy) and the Benjamin Franklin Medal in Physics. Cornell has also made contributions in the field of atom optics, including developing techniques for guiding beams of atoms through microscopic channels in hollow glass fibers.

Carl Wieman, a professor in the University of Colorado Physics Department and a Fellow of JILA since 1984, is internationally known for his work on parity violation in atomic cesium and for his experiments in laser cooling. He is a recipient of numerous international prizes and awards. Wieman and Cornell have collaborated on the Bose-Einstein Condensation project since 1990.

Mike Anderson did his graduate work at the University of Colorado and joined Cornell's group as a postdoctoral fellow in 1993. He left in 1996 to join Meadowlark Optics in Frederick, Colorado; he is currently Vice President of Engineering there. Mike Matthews and Jason Ensher were graduate students in the University of Colorado Physics Department. Matthews is now a staff scientist at 3M in Austin, Texas, and Ensher is currently doing postdoctoral research in ultra-cold molecular physics at the University of Connecticut in Storrs.

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