CARL E. WIEMAN

BOSE-EINSTEIN CONDENSATION, A NEW FORM OF MATTER AT A TEMPERATURE NEAR ABSOLUTE ZERO

JOOK T.M. WALRAVEN

NEW LEVELS OF CONTROL AT LOW TEMPERATURE

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NWO/Huygens Lectures

The Netherlands Organization for Scientific Research NWO and the newspaper *NRC Handelsblad* have organized NWO/Huygens Lectures since 1992. The NWO/Huygens Lectures are a series of lectures, providing the public at large a unique opportunity to listen to and meet famous scientists. The city council of The Hague acts as a host.

For the year 2000 lecture, NWO invited the American physicist Carl E. Wieman, Distinguished Professor of Physics at the University of Colorado. Wieman is primarily known for using laser light to cool and hold atoms and for measuring the breakdown of mirror reversal symmetry in atoms. In 1995 his research led to the attainment of the long-sought Bose-Einstein condensation in a vapour.

The successful NWO/Huygens Lectures are being organized for the ninth time. Predecessors of Professor Wieman were in their field equally famous. For the 1999 lecture NWO invited the American neurologist Antonio R. Damasio of the University of Iowa, who developed a new notion about the interaction between emotions and feelings with rational behaviour. The Dutch Professor Fernando H. Lopes da Silva (University of Amsterdam) acted as co-lecturer.

The series started with a lecture of Professor Nathan Glazer (Harvard University) about ethnic minorities. He was followed in 1993 by Professor Bert Bolin, president of the Intergovernmental Panel on Climate Change. The 1994 lecture, about soft materials, was given by Nobel Prize winner in physics Professor Pierre-Gilles de Gennes, from the Collège de France. In 1995 Professor Jonathan D. Spence (Yale University) talked about Chinese and Euro-American relationships. In 1996, the winner of the 1997 Nobel Prize in Medicine, Professor Stanley B. Prusiner (University of California) talked about his prion concept on the spongiform brain diseases in animals and humans like scrapie, BSE and Creutzfeldt-Jakob. Then, in 1997 the paleo-ecologist Professor Paul Colinvaux of the Smithsonian Tropical Research Institute (Panama) lectured about his research on biodiversity in the Amazone area and, finally, in 1998 Professor Tony Hoare (Oxford University) discussed the theme of the science of computing and the engineering of software.

Carl E. Wieman grew up in the forested mountains of Oregon in the USA. He went on to obtain his B.S. from the Massachusetts Institute of Technology in 1973 and his Ph.D. from Stanford University in 1977. He has been at the University of Colorado since 1984 where he is currently a Distinguished Professor of Physics. He has used lasers to study and manipulate atoms in a variety of ways, but is primarily known for using laser light to cool and hold atoms and for measuring the breakdown of mirror reversal symmetry in atoms. The latter work probes the fundamental forces in nature with extreme sensitivity. As part of the former work he discovered and circumvented many of the practical and fundamental limitations of laser cooling. This led to work on combining laser and magnetic trapping of atoms and cooling them sufficiently to attain the long-sought Bose-Einstein condensation in a vapour in 1995. He has received numerous international awards in recognition of his work including election to the National Academy of Sciences of the USA and receiving the Lorentz Medal 1998 of the Royal Netherlands Academy of Arts and Sciences in 1999.

J.T.M. Walraven (Jook) was born in Amsterdam, the Netherlands in 1947. He studied physics at the University of Amsterdam (UvA) where he received his PhD in 1982 on the topic “Stabilization of Spin-polarized hydrogen and Deuterium”. He was employed by the Dutch foundation for fundamental research of matter (FOM) and the UvA where he became professor of experimental statistical physics in 1988. He was visiting professor of physics in Grenoble, Kyoto and Paris. In 1995 he received the Prix Franco - Néerlandais Descartes - Huygens for his work on ultracold gases, in particular hydrogen. Since September 1996 he is director of the FOM institute for atomic and molecular physics (AMOLF) in Amsterdam. Active research activities: quantum gases, physisorption at ultra-low temperature, properties in two-dimensions, collisional relaxation phenomena, antihydrogen, optical cooling and evaporative cooling.

Carl E. Wieman

Bose-Einstein Condensation, a New Form of Matter at a Temperature near Absolute Zero*

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Abstract In 1924 Einstein predicted that a gas would undergo a dramatic transformation at a sufficiently low temperature. In 1995, my group was able to first observe this transformation (now known as Bose-Einstein Condensation or BEC) by cooling a gas sample to the unprecedented temperature of only 100 billionths of a degree above absolute zero. The BEC state is a novel form of matter in which a large number of atoms lose their individual identities and behave as a single entity. This entity is the atom analogue to laser light, and, although large enough to be easily seen and manipulated, exhibits the non-intuitive quantum behaviour normally important only at much tinier size scales. The study and use of the curious properties of BEC has now become an important sub-field of physics. I will discuss the techniques used to cool atoms to create BEC and some of the subsequent research on it.

A new form of matter Since I use laser light for all my research it is a particular honor to give the Huygens lecture, because Huygens was responsible for providing much of our understanding of light. In this lecture, I will talk about a new form of matter whose existence was proposed by Albert Einstein in 1924, and then it was finally first created in June of 1995 by a research group at JILA/University of Colorado led by myself and Eric Cornell. It has now been duplicated and studied all over the world. This new matter is formed by cooling a gas to almost inconceivably low temperatures, far colder than ever occur in nature, and it has a variety of strange and fascinating characteristics. It magnifies the strange world of quantum physics from the extremely tiny size scale up to something easily observed and manipulated.

Absolute zero Since this is all about very low temperatures let me start by talking about what temperature is on the microscopic size scale. Temperature is simply the motion of atoms. In a gas, higher temperature corresponds to the atoms moving faster and lower temperature means that they are moving more slowly. To cool a gas one must slow down all the atoms. With this picture in mind it is easy to see that there is a coldest possible temperature. This corresponds to all of the atoms being stopped. Physicists call this absolute zero, and it corresponds to –273 centigrade. The coldest place that occurs in nature is the cold depths of interstellar space. This is at a temperature of 3 degrees above absolute zero due to the heat left over from the Big Bang at the creation of the universe. Although this seems very cold by our earthly standards, it is millions of times too hot for BEC. To cool atoms to BEC temperature, less than one-millionth of a degree above absolute zero, they must be slowed literally to a snail’s pace. Fortunately one thing physicists are able to do much better than nature is get things very cold, and in fact BEC in a gas owes its existence to this fact. It can never occur naturally.

Holland has played a major role in developing this capability of reaching very low temperatures. This grew out of the famous work of Kamerlingh Onnes and his laboratories in Leiden. For many years the coldest temperatures that could be achieved were in his labs, and many Dutch research groups including that of Professor Walraven have continued this tradition of low temperature research. Since K. Onnes achieved temperatures less than what can be found in nature his lab may have been the coldest spot not only on earth but in the entire universe! Now our labs in Boulder have taken over this extravagant claim. As you can see by comparing this picture of Boulder with Holland, different geography is no barrier to doing research on ultralow temperatures!

Bose-Einstein Condensation Why are we so interested in getting things cold? It has to do with quantum mechanics and Einstein. If you put some atoms of gas in a container, such as the bowl in **figure 1**, quantum mechanics says that they are not allowed to have just any speed. The atoms

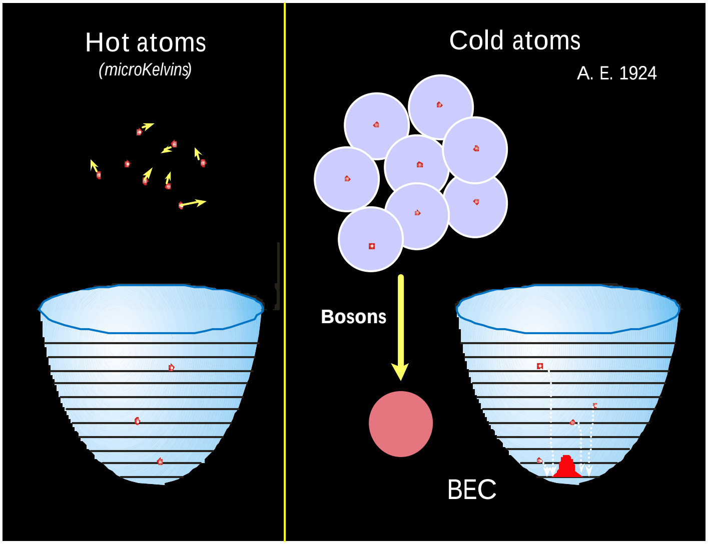


Figure 1. Bowl showing the discrete energy levels allowed. At the top are hotter atoms distributed over very many levels. On the bottom, when the DeBroglie waves of the atoms start to overlap a large fraction of the atoms all jump into the bottom energy level.

are permitted to have only particular energies or speeds. However these allowed energies are almost infinitesimally close together in any real container. So as long as the gas is “reasonably warm”, which by my standards is 10 millionths or so of a degree above absolute zero, one never notices this discreteness of possible energies. The gas atoms behave much as little balls flying around and bouncing off each other. They are distributed over countless different energy levels. However, if you start to get the gas seriously cold, down to less than a millionth of a degree, something very strange happens. This was predicted by Einstein in 1924 just by looking at the equations. He recognized that these equations said that, if the atoms were cooled to extremely low temperatures, at a certain temperature suddenly a large proportion of the atoms would jump down into the single lowest possible energy level of the container. This is known as Bose-Einstein Condensation or BEC. As the atoms get colder, their inherent “quantum mechanical waviness” or DeBroglie wavelength gets larger. The point where BEC begins to form is when these atom waves get so big they start to overlap. The temperatures required are much less than one millionth of a degree above absolute zero, and so Einstein never took this prediction of such a strange behavior very seriously.

BEC is a very strange material in a number of respects. First, there are a large number of atoms in a single energy level. As such, the atoms are indistinguishable in every respect, even occupying the same position in space! Since they are fundamentally indistinguishable they cannot even be considered as separate atoms. They have lost their identities as independent atoms, and have now fused into a sort of “superatom”. Second, BEC represents a large enough chunk of material to easily see and manipulate, but it is entirely quantum mechanical in its behavior. Thus it displays the unusual nonintuitive behavior that we usually only associate with the submicroscopic quantum world.

Although Einstein’s original concept of condensation of a very cold gas was never realized until 1995, there have been three other major examples of such macroscopic quantum behavior. These are: superconductivity, a phenomenon discovered by K. Onnes in which all electrical resistance vanishes in certain low-temperature materials; superfluidity in which all the viscosity vanishes in sufficiently cold liquid helium; and laser light. We now understand the two “supers” as connected with BEC, although they are very different from the atoms in a gas envisioned by Einstein. These three phenomena are probably the three most remarkable things that physicists have created and so much of our motivation in trying to get BEC in a gas was the hope that we would add a fourth member to this remarkable family with some of the same exotic characteristics.

How we made BEC Having provided a background on what BEC is and why we were eager to make it, let me now turn to how we actually made it. In contrast with many of the pioneering experiments in physics these days, this does not require a very large or expensive apparatus. The heart of the apparatus for this experiment is shown in **figure 2**. It is just a small glass cell from which all of the air has been evacuated, and inside of which we put a small amount of rubidium atoms. There are coils of wire around the cell that we run current through to produce magnetic fields. Laser light from inexpensive diode lasers like the type in a CD player or a laser pointer are sent through the cell walls. This heart of the apparatus is about the size of my fist. It sits on a table in the lab, and most of the rest of the table is covered with the lasers and their associated optics. The rubidium atoms in this small glass cell are cooled using a combination of two different technologies I shall explain below: first laser light is used to cool and hold

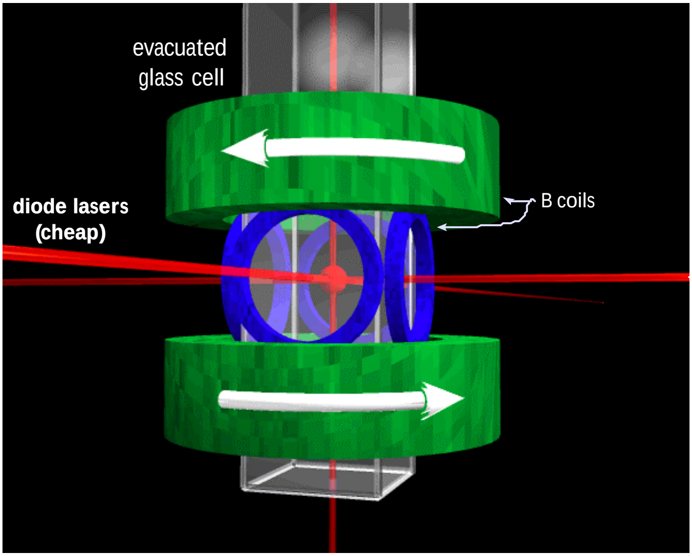


Figure 2. BEC apparatus. A rectangular glass cell (2.5 cm square by about 10 cm high) is attached to a vacuum pump and rubidium reservoir (not shown). Laser beams coming from all six directions go through the cell. The magnetic fields are produced by the two large coils and the four smaller coils.

the atoms, and then we use something called magnetic trapping and evaporative cooling. Before I explain these I should point out that other physicists complain that I make this sound much too cheap and easy. So let me emphasize that while it can be rather inexpensive, that is not the same as "easy". It took us many years to make all this work. During the cooling process one must do many things to the atoms and they must always be handled with exquisite gentleness!

The first step of cooling uses laser cooling and trapping. Over the last 25 years, a number of research groups have been actively developing remarkable new capabilities for using laser light to both cool and confine ("trap") atoms. While many of these ideas and techniques are incorporated into our experiment, here we will mention only the most basic. The primary force we use is the radiation pressure force, produced when one bounces light off of the atoms. The atom scatters the tiny particles of light called photons. Each time the atom scatters a photon, it feels a tiny kick due to the transfer of momentum. Lasers allow us to scatter a very large number of photons and thereby exert a substantial force. This is much like pushing a bowling ball by throwing many table tennis balls at it. This is adequate for pushing atoms around, but to cool the rubidium atoms in our glass cell, we must not just push on them: we must also slow them down no matter what direction they are moving. To do this we send light into the cell from all six directions, and by adjusting the color of the laser light to exactly the right value (slightly redder than the color the atom most likes to scatter) the atoms always feel the light preferentially opposing their motion, no matter what direction they are moving. This is illustrated in the demonstration applet by adjusting the color of the light. [optical molasses applet of BEC in P2000]. Thus, as shown in the demonstration applet, many of the fast moving atoms in the cell can be slowed and held in this "optical molasses". (Of course, the real atoms are much smaller and are initially moving at about 1000 Km/hr.)

When we first accomplished this we were very excited to be able to use laser light in this way to cool atoms down to just a few millionths of a degree above absolute zero. However, we then became curious about what limited the temperature and density of these cooled atoms. Why did they not get even colder and closer together? We discovered that there were several processes but they all involved the photons "hanging around" too long. The photons are sort of like houseguests. When they first arrive they are very nice to have—they are useful for cooling and holding the atoms. However, if they hang around too long, which they do by bouncing back and forth between the cold atoms, they are unpleasant. They keep jiggling the atoms around and this jiggling motion prevents the atoms from becoming even colder. Once we discovered this of course we wanted to eliminate these photons to try and get even colder.

It is much easier to get rid of photons than it is houseguests who have overstayed their welcome; one can simply block the laser beam. Unfortunately, the cold atoms then just fall like little rocks, and when they hit the bottom of the apparatus they stick and the experiment is over. To keep them from falling and being lost in this way, we then turn on the current through the magnetic field coils **figure 2**. This exerts a force on the tiny bar magnet that is contained in each atom, and by properly shaping this magnetic field, we can form a sort of “magnetic bottle” that holds the atoms. This magnetic bottle is the world’s best thermos bottle. It holds these extremely cold atoms just one centimeter away from the hot room temperature walls without allowing the atoms to heat up. It also allows us to use a technique known as evaporative cooling to further cool the atoms. This technique had come out of the extensive work that had been done on hydrogen in an effort to achieve Bose-Einstein Condensation. A number of groups had been pursuing this goal in hydrogen over the last 25 years with the leading groups being those of Kleppner and Greytak at MIT, and Walraven and Silvera at Amsterdam. Many of the key ideas, particularly those of magnetic trapping and evaporative cooling were guided by that earlier research. The theoretical work on the behavior of atoms at very low temperatures done by B. Verhaar’s group at Eindhoven also played a major part in guiding our efforts to evaporatively cool rubidium atoms.

The physics of evaporative cooling is familiar to all of you since you encounter it every time you get a cup of hot coffee. The steam you see is the most energetic coffee molecules leaping out of the cup taking away more than their share of the energy, so the ones left behind get colder. In our magnetic bowl the same thing happens to the atoms as the most energetic ones escape over the lip of the bowl. As the remaining atoms cool, they settle down towards the bottom of the bowl. However, as shown in the demonstration applet [BEC evaporative cooling applet] after a short time no more escape and then the temperature stops decreasing. To avoid that, we effectively slowly lower the lip of the bowl as I can demonstrate with the applet so that we continuously skim off the most energetic atoms. This must not be done too fast or it will let all the atoms escape, but not too slow or the atoms will not cool enough. So our students spent many hours in the lab doing much the same as one does with this applet: trying to bring the lip down at the best rate to get the atoms to Bose-condense while leaving as many atoms as possible. In fact this process takes just about as long in the lab as the applet requires, approximately a minute.

What does BEC look like? Of course, BEC does not look like the pulsing object in the applet. To see what it really looks like we take a "shadow snapshot" of it as shown in **figure 3**. This is done by sending in a short pulse of laser light. The little blob of atoms absorbs the light and thereby makes a shadow in the laser beam. We image this shadow onto a TV camera, and then are left with a two-dimensional shadow image of the blob. The actual data are little two-dimensional black and white shadow pictures, but we dress them up by using computer processing to make them three dimensional and give them false color. (One should never underestimate the value of making your data look attractive if you want people to pay attention to it!) These images show the density of atoms at the bottom of the magnetic bowl. Shown here in **figure 4** are three images taken as we make the sample colder and colder. We actually have much better data now with many more atoms in the clouds, but I show this data for historical and sentimental reasons since it was the first data that showed we had made BEC. Also it is rather unique for physics data in that it has achieved "celebrity" status, having appeared in TV shows and on the covers of newspapers, magazines, books, calendars, and even T-shirts!

So what is this celebrity data actually showing us? In the left-most picture, we have cooled the atoms down to a tepid 400 nK (400 billionths of a degree above absolute zero), and what we see is a round hill, which

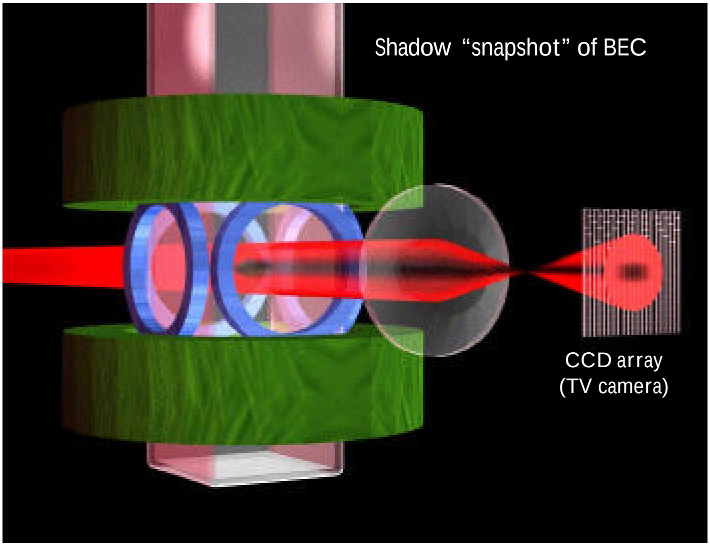


Figure 3. Setup for taking image of BEC. A laser beam is flashed on and the BEC casts a shadow in this beam that is imaged onto a TV camera by a lens.

looks like the familiar distribution of atoms one would have in any normal gas in such a bottle. The middle picture shows a cloud of about 10,000 atoms that has been cooled down to about 200 billionths of a degree. On top of the rounded hill, a narrow spire, corresponding to a large number of atoms very close together, has emerged. When we cooled even further (right), we produced a sample (~2000 atoms) in which the gentle hill is completely gone, and only the narrow spire remains. This narrow spire corresponds to a large group of atoms that are densely packed together and almost completely stationary. This is much like seeing a water droplet condense at the bottom of a container of water vapor as it is cooled. In the same way that the appearance of the drop signifies a phase transition in the water, here this spire indicates that the atoms have undergone the BEC transition.

This can be understood by returning to our original picture of BEC as atoms piling up in the lowest energy state of the container. The normal atoms that are distributed over many energy levels in the magnetic bowl form the gentle hill that is observed in an ordinary gas. The atoms that have dropped into the single lowest possible energy state of the magnetic trap form the very narrow peak. Since the atoms in this energy level are the most localized, they give a narrow spire at the center of the cloud.

A new kind of physics This was observed in our lab in June of 1995, and since then there has been an enormous amount of research on BEC in gases. There are now about two dozen research groups around the world, including at least one here in Holland, that are making BEC in a variety of different atoms. There are countless theorists that are busy predicting properties of the condensate and suggesting new experiments, much faster than we poor experimenters can keep up. Well over 1000 research papers have been written on BEC, with a new one appearing every one to two days! What is the reason for this tremendous interest in this subject in the physics community? Although most physicists will give you complicated technical justifications for their research, I think that the fundamental reason is simply illustrated by **figure 4**. This image of BEC is a real picture of a quantum wave function! Quantum wave functions are something that every physicist has known about but always as abstract concepts that we can only infer from experiments that probe matter at tiny distance scales, the size of atoms or smaller. But here we have gigantic wave functions that we can directly see and manipulate. Okay, so it is not that gigantic; it is about the size of a hair, but that is still big enough to easily see and poke, and is big enough to put wave functions, with all their weird and marvelous properties that we have been studying for the past hundred years, on a much more

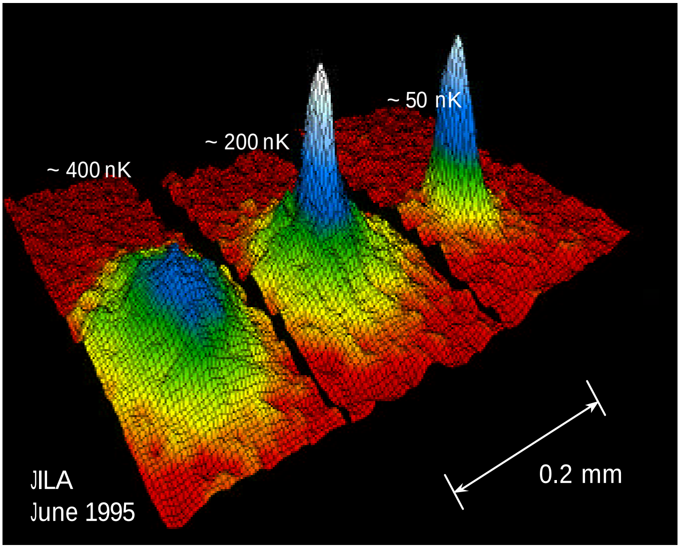
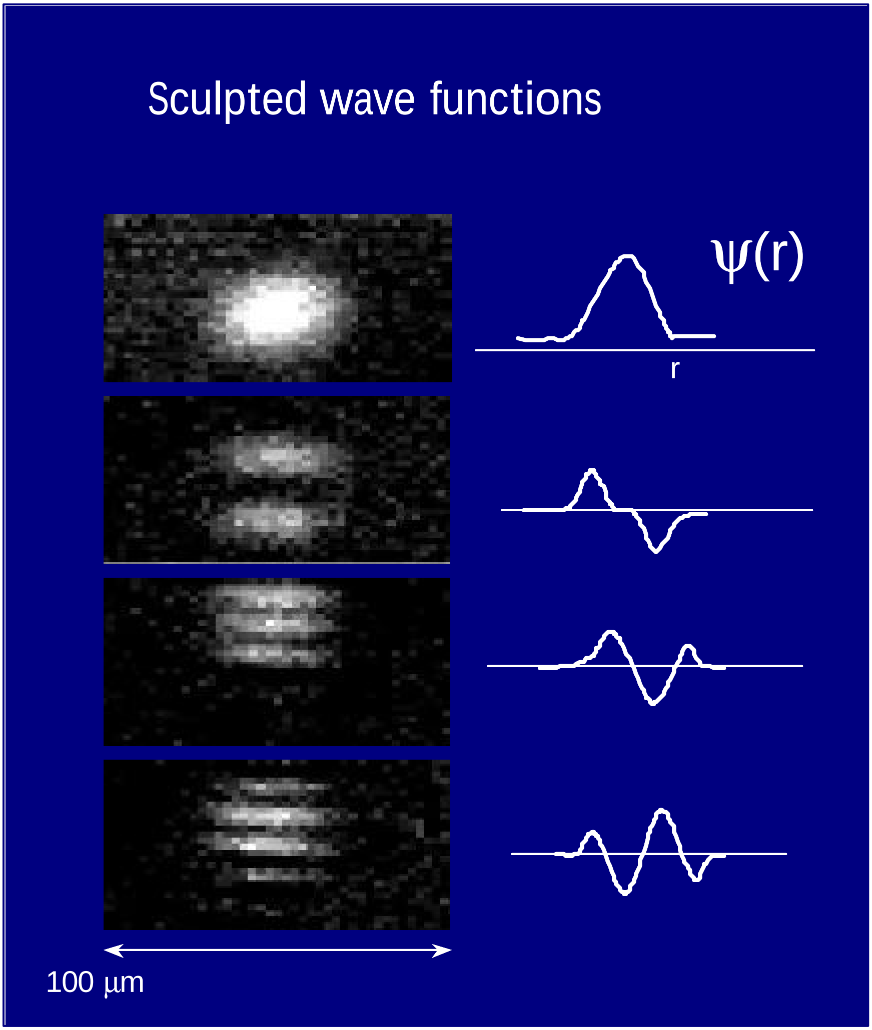


Figure 4. False color images of the cold cloud. The temperatures of (left to right) are 400, 200, and about 50 billionths of a degree (nK) above absolute zero. The vertical axis is the density of atoms.

tangible human scale. And many of these properties are truly remarkable. For example, by putting one condensate on top of another we can get interference between them as if they were waves. So by adding one little blob of atoms on top of another, we can make the atoms that were in certain regions of space vanish! However, being able to see and manipulate wave functions allows us to do much more than simply make nice demonstrations. It allows us to explore basic quantum physics at a level that has not been possible before. We can do all sorts of experiments where we poke and prod our wave functions and then see how they behave. This is a kind of physics that has not been possible before, and it has allowed many different aspects of BEC to be studied. Such things as the condensation temperature, how the BEC vibrates like a bowl of jelly when poked, how mixtures of two kinds of condensates mix and separate, and many other more technical characteristics. In general, properties that reflect the stable structure of the condensate without any noncondensed atoms around match the theoretical predictions quite well. This is not surprising because this is quite similar to the sorts of quantum physics we study in the structure of atoms and molecules. However, quantum properties that involve dissipation; the interaction of the quantum wave function with those atoms in the bowl that have not condensed have in most cases turned out differently than predicted. This is a quantum regime we have not been able to study before, and it shows that nature is often cleverer, or at least more subtle than physicists at their first try at understanding things. Now by doing experiments and adapting our theories on the basis of these experiments we are mastering these subtleties.

The latest discoveries Rather that give an inadequate coverage of what is now a large field, I would like to end by discussing two areas of research currently being pursued in our lab. These are just to give you examples of the sorts of things that are being studied and discovered with BEC.

The first area of research is built around the capability that we have developed for “sculpting” BEC wave functions. This has allowed us to create wave functions with a variety of shapes and rotation. The details of how we do this are a bit complicated and involve various combinations of laser and magnetic field to build up the wave function piece by piece. The basic concept is much like making an ice sculpture by putting a cold probe into a tank of water and freezing little chunks of water to slowly build up the desired shape of ice. One nice example of this that will be appreciated by the members of the audience that have taken a course in introductory quantum mechanics is shown here in **figure 5**. In such a class every student is shown wave functions corresponding to the first few levels of a harmonic oscillator potential (a parabolic shaped bowl). However, these pictures shown in the textbooks are always theoretical constructions. Here we have created condensate wave functions that actually have these shapes and we take real photographs of them. This is a cute example that appeals physics students, but the real reason for developing this technique is to answer some important scientific questions. We are using it to create quantum vortices and study their properties. Big vortices, like hurricanes, are familiar to everyone. Quantum vortices are wave functions that have the smallest nonzero amount of rotation allowed by quantum physics. These vortices are very important in the behavior of superconductors, so it would be nice to understand them better. This can be done in BEC because we can make them large enough to observe in detail for the first time. The slides show a picture of such a vortex. One of the big questions was how long they live and how the process by which they die. As shown in the slides we can make a vortex and watch it die by having the core slowly spiral out to the edge and disappear. By carefully measuring the time this takes to happen and the dependence on conditions such as temperature we can sort out which theories that attempted to predict the lifetime and decay processes are right and which are wrong.



Sculpted wave functions

Figure 5. Images of sculpted wave functions constructed to look like the wave functions of the first four levels of a parabolic shaped potential. On the left are the images of the condensates for each shape containing about 500,000 atoms each, while on the right are cross sections of the condensate.

The other area of research that we are working on is very exciting because it opens up a large new territory for study and it has produced such dramatic and surprising results. This research involves the new capability to adjust the “self-interactions” within a condensate. The different parts of the condensate wave function exert forces on each other, and this force we call the self interaction. If the force is repulsive, it means the different pieces are pushing out on each other, and so this makes the condensate wave function get fatter as you add atoms to it. When the interaction is attractive it means all the pieces are pulling in on themselves, and so it causes the condensate wave function to shrink in size as one adds more atoms. For the attractive case, if one adds too many atoms the wave function was thought to implode in on itself in some manner. The equations predict that it can no longer exist. Both the strength and the sign of the self-interaction depend on the type of atom in the condensate. For the first four years of BEC, we physicists were limited to a single value for each atom.

Change the self-interaction in the BEC In the early 1990’s, well before condensates had been created, B. Verhaar proposed that it should be possible to change the self-interaction in the BEC for certain atoms by putting them in a magnetic field of exactly the right size. This was based on his theoretical calculations. (Being a theoretical physicist of course he was happy to make this prediction without worrying about the fact that BEC had never been created!) Once we could make condensates routinely we started thinking more about this idea and were very intrigued by it. The capability to adjust how a wave function interacts with itself and study the subsequent behavior is something physicists have never been able to do. It offered a new territory and new opportunities for better understanding and controlling BEC and quantum mechanical behavior in general. So we eagerly set out to achieve it. As it turned out, it was a major struggle to actually find an atom that had the particular properties needed for an adjustable self-interaction and get it to Bose-condense. What the theorists did not warn us about was that connected with this marvelous property of adjustable interactions are many nasty features that make it technically much harder to get any suitable atom to condense. These atoms are much more prone to heating up and escaping out of our magnetic bowl. However, after several years of work we finally succeeded with the rubidium 85 isotope. This is just like rubidium 87 that we used for all our other BEC work, but it has two less neutrons. This has a tiny effect on all the normal properties of the atom, but it changes its behavior at ultralow temperatures very dramatically. So finally we were able to overcome all the obstacles and managed to get the 85 rubidium atoms to form a BEC in which we could

adjust the self-interaction. One measure of the difficulty of achieving BEC in 85 is that we have to cool it to about one hundredth the temperature that we used to get BEC in 87, namely down to about a billionth of a degree above absolute zero! However, having finally succeeded in making it we now have the marvelous capability to study how it behaves when we change the self-interaction. This is rather like struggling up over a high mountain pass to finally reach a lush new unexplored valley. (Although this analogy may be more meaningful to my audiences in Colorado than those in Holland.)
So what sorts of experiments are we doing? In **figure 6** we show how we can change the magnetic field to make the interactions more repulsive and thereby cause the condensate/wave function to get larger. The changes we observe agreed nicely with the predictions. There are lots of predictions and many questions about what will happen as we continue to change the field farther in that direction to make the interactions extremely large. We are eagerly looking forward to doing those experiments.

Unexpected surprises However, we have not yet gotten to those experiments because of what we discovered when we went in the other direction and made the interactions attractive. Here again there were many predictions and virtually no data about exactly how the condensate would implode in on itself as the self-interactions were made increasingly attractive. From the point of view of an experimenter, the ideal situation is one where there are many competing theoretical predictions that have already been made and we get to act as the ultimate authority to judge who is right and who is wrong. And when we tried the experiment we got the results that makes an experimenter the happiest, namely none of the predictions were correct! Nature once again proved to be cleverer than physicists, and showed us that there are still unexpected surprises waiting to be discovered. (Of course the theoretical physicists are pretty clever and so this does not happen very often, which is why it is so much fun when it does occur.) Anyway, we observed a very dramatic and surprising result. As the interaction was made more negative the condensate shrank down to a smaller and smaller size, and then suddenly there was a dramatic explosion in which a large fraction of the atoms were blown away. However, as unexpected as the sudden explosion was, what was even more surprising was that about a third of the atoms remained in a cold little condensate, while 30% of the atoms came exploding out in a cloud that was only about 50 billionths of a degree above absolute zero. Although much hotter than the condensate remnant, this is much colder than the other obvious energy scales, such as the binding of atoms to form molecules, in the problem. This collapse and subsequent

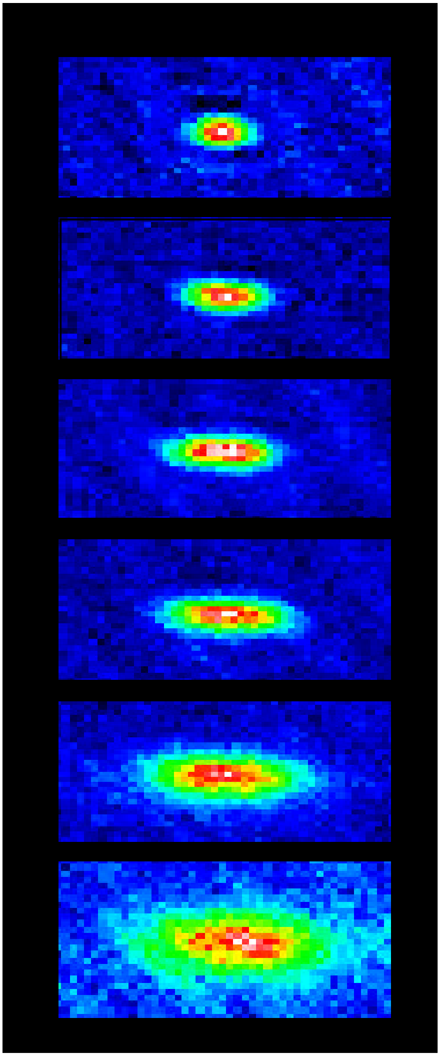


Figure 6. Pictures of the BEC as the interaction is increased by changing the magnetic field from 165 G (top) to 156 G (bottom). The increasing self-interaction causes the BEC to expand.

explosion looks surprisingly similar to what happens in a supernova where a star collapses in and then produces an exploding shell of hot gas while leaving a small cold neutron star behind. So we call our condensate behavior “Bosenovas”. Of course, the physics of the two events are very different and the energy scales are almost unimaginably different. We are currently taking more data and trying to learn more about the Bosenova behavior so that we can understand it. Particularly puzzling is the source of the 50 billionth of a degree cloud and the physics that would cause this cloud to form without boiling away the much colder condensate remnant. Although these are major puzzles at the moment, because we now have such exquisite experimental control over this system and can observe what is happening in such detail, and there are so many smart theorists trying to make sense of this behavior, I am sure we will understand it soon. However, this illustrates why the study of BEC is so rewarding for physicists. We are able to explore new territories where there are many interesting new surprises awaiting us, but because we can see what is happening so clearly we can quickly understand and utilize these new discoveries.

What comes next? Let me now conclude by briefly discussing what comes next in BEC research, and the closely connected question that most nonscientists have: what is it good for? From a pure physics research standpoint, what comes next is to continue to explore the properties of BEC with the sorts of experiments I just discussed. As well as understanding more about this strange new form of matter, this knowledge also broadens our understanding of some aspects of basic quantum physics that are likely to be important both in electronic circuits as their sizes approach the quantum scale and in the ongoing effort to build a new radically new type of computer called a “quantum computer”. However, at this time it is primarily just basic research driven by curiosity.

Nonetheless, there are reasons to believe that BEC may some day have real applications. This is likely to be many years, perhaps even decades, from now, but I believe that condensates are likely to be useful because of their similarities to laser light. The fundamental property that makes laser light useful is that all the light is acting exactly the same way, and this allows us to control that light much better than we can the light from a regular light bulb. It is this property that makes lasers so good for surgery, for sending telephone signals down fibers, and a whole host of other uses. BEC is the exact atom analogue of laser light, with all atoms behaving exactly the same. For this reason we can also control the atoms of a BEC far better than we can atoms from any other source. We can put them exactly where we want them with exactly the energy we want. In fact, our control is so good that it is limited only by the uncertainty principle of quantum mechanics.

Where might this improved level of control prove useful? The first applications are likely to be in certain very sophisticated instruments such as better atomic clocks and extremely sensitive devices for measuring magnetic or gravitational fields. Such uses of BEC are already being seriously contemplated and will likely happen within a few years. However, I recognize that not many people are likely to have atomic clocks on their mantle so this is not exactly a widespread use. On a longer time scale, though, it does seem quite possible that BEC may be used to even make home electronics. Looking at the current development and miniaturization of electronics it seems likely that one day circuits will be constructed by putting individual atoms exactly where they are needed. At that point, the exceptional control of atoms provided by a BEC may well make it a key construction tool. Of course there are enormous engineering hurdles to be overcome before this is practical, but the similarities to the laser and its value make me optimistic that some day BEC will also become more than an exotic toy for physicists.

The demonstration applets used in this talk, plus many others and additional explanation can be found at the website http://www.colorado.edu/physics/2000/index.pl The particular applets used are in the Bose-Einstein Condensation section which is part of the Atomic Lab section.

JOOK T.M. WALRAVEN

NEW LEVELS OF CONTROL AT LOW TEMPERATURE

Abstract The observation of Bose-Einstein Condensation (BEC) in 1995 by Eric Cornell and Carl Wieman has resulted in a profound confrontation of the knowledge of two major fields in physics: the physics of atoms in radiation fields (quantum optics) and the physics of many-particle systems at low temperature (quantum fluids). The concept of BEC dates back to 1924 when it was proposed by Albert Einstein as the daring consequence of the analogy between light waves and matter waves when applied to a gas of atoms at low temperatures. Although the analogy is appealing it has its limitations: atoms interact (collide), photons don't. From the quantum optics point of view these interactions provide the fundamental limitations in precision measurements (for example in atomic clocks); from the point of view of the quantum fluids they enable unprecedented control over the properties of quantum systems. In my contribution, I will address the impact of Bose-Einstein Condensation with examples to illustrate various points of view on this discovery.

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

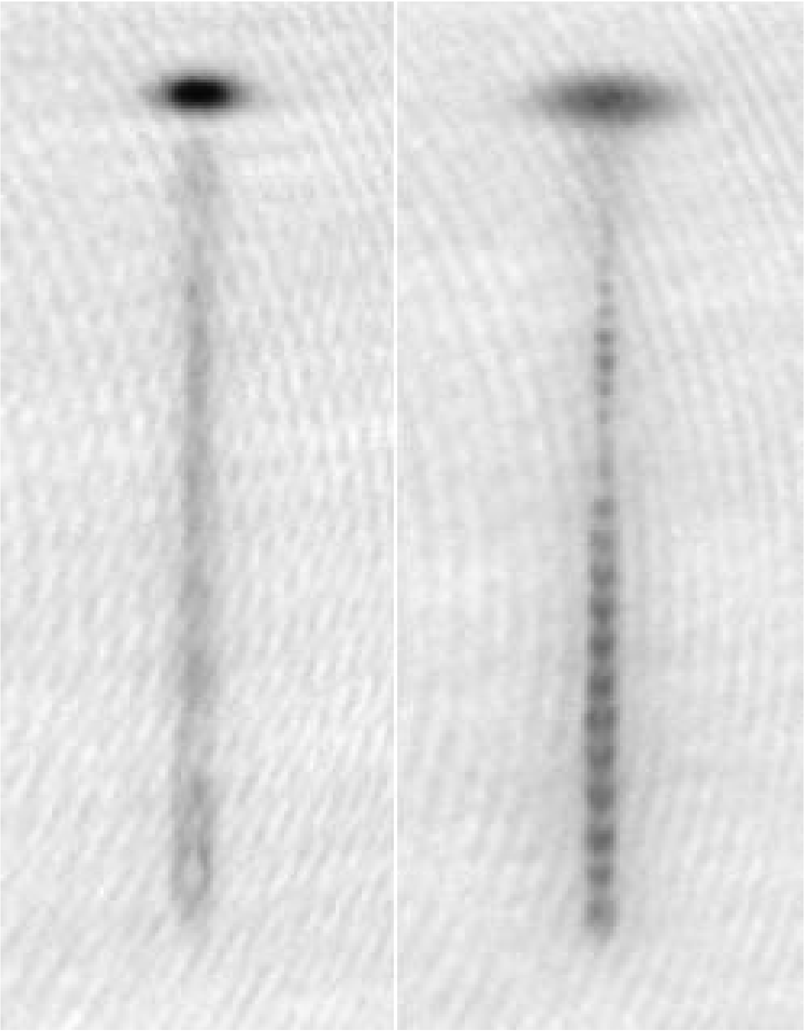


Figure 1. (a-left) Atomic beam (atom laser) coupled out of a Bose-Einstein condensate using a radio frequency magnetic field in combination with gravity. (b-right) two overlapping beams coupled from different parts of a condensate and showing interference.

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.

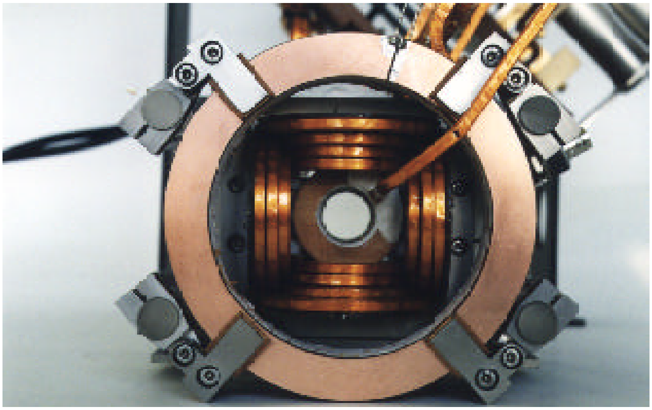


Figure 2. Magnetic trap used to confine Bose-Einstein condensed samples at the FOM institute AMOLF.

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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