THE 1997 KING FAISAL INTERNATIONAL PRIZE
I n June 1995 our research group at JILA/University of Colorado first observed Bose-Einstein condensation in a gas of very cold rubidium atoms.\(^1\) This was the result of efforts of a substantial group of students, postdoctoral scholars, and JILA faculty who had been working on BEC for seven years, with the two of us as the co-leaders. These included C. Monroe, N. Newbury, C. Myatt, C. Sackett, J. Cooper, M. Holland, R. Ghrist, W. Petrich, E. Burt, M. Anderson, J. Ensher, D. Jin, and M. Matthews. In this paper we will briefly review how the efforts of this team succeeded in achieving BEC.

There are two general classes of particles (including atoms) in nature. These are named after two famous physicists, E. Fermi and S. Bose. Particles of one class are called fermions. A basic law of physics says that two fermionic atoms of the same type cannot be in the same place moving with the same speed ("occupying the same quantum state"). Particles of the second type are called bosons. Bosonic-type atoms like to all be the same (in terms of speed, ‘energy level’, and position) but this affinity is apparent only under very special conditions, usually associated with very low temperatures.

When a gas of atoms is placed in a container, the laws of quantum mechanics say that each atom can have one of only certain discrete possible energies (or speeds) called ‘energy levels’. However, the difference between these different energy levels is incredibly tiny and hence quite undetectable in normal containers. There are far more possible levels than there are atoms, so it is unlikely that two atoms are of the bosonic type and hence allowed to be in the same level, or not. However, in 1924\(^2\), Einstein predicted that if bosonic atoms were cooled to extremely low temperatures, a large proportion of the atoms would go into the single lowest possible energy level of the container. This is
substantial force. This is much like pushing on a large heavy ball (the atom) by bouncing many small balls off it. To cool the atoms, we must slow them down. To do this using laser light we must make this photon scattering force depend on how fast the atoms are moving. For this we use the Doppler effect. This is the effect that causes a whistle to sound higher in frequency if you are driving towards it in a speeding car than it does if you are stationary. In the same way, the atoms see the light at a different (bluer) colour if they are moving towards a beam of laser light than if the atoms are stationary. If the laser is adjusted to make the light that is shining on the atom exactly the proper colour, the atoms will scatter more photons and therefore feel a larger force when they are moving than if they are stopped. Thus, if laser beams come from all six directions to strike the atom, the net effect is that no matter what direction the atom is moving it will always feel a force opposing its motion and thereby slowing it down. Thus, all the atoms are slowed and the sample is cooled.

Laser light can also act as ‘optical insulation’ to prevent the cooled atoms from touching the room temperature walls of the container they are in and being heated by conduction. To accomplish this, the photon scattering force is arranged so that it pushes the atoms to a particular point in space and thus holds the atoms there so that nothing touches them but the laser light. This is called laser trapping.

The simplest way to implement laser cooling and trapping, and the way we use it in the BEC experiment, is a ‘magneto-optic (MOT) trap in a vapour cell’. The vapour-cell trap was invented by our group a few years before we started trying to create BEC. It is useful for many different kinds of experiments on very cold atoms. To make this trap, a small glass cell is evacuated so that all the air in it is removed and then a very small amount of rubidium gas is put in it. The laser trap is created by sending in laser beams with the proper characteristics (colour and polarization) from all six directions. Only a small amount of light is needed, so we obtain this from small diode lasers, the same type of laser that is used in CD players and laser printers.

This laser trap captures the slowest atoms in the gas. A short time after we turn on the trap, it contains about 10 million atoms and has cooled them to a temperature of about 10 millionths of a degree above absolute zero. This is an easy but very large step towards BEC. Unfortunately, it still leaves the atoms much too hot to achieve BEC. The reason the atoms remain too hot is because the photons bouncing off and colliding with other atoms prevents them from getting cold enough or close enough together. The study of this process was actually what got us started working on BEC. To eliminate these undesirable effects of photons, after cooling we shut off the laser beams and then held the cooled atoms in a purely magnetic trap. A magnetic trap confines the atoms using a magnetic field to exert a force on the tiny bar magnet that is contained in each atom. To accomplish this, the magnetic field must have the proper spatial variation and be fairly strong. Although this force is too weak to hold atoms if they are at room temperature, it is strong enough to confine them easily once they have been laser cooled.

After successfully demonstrating that we could hold the very cold atoms in magnetic traps, we began to try to cool them further, all the way to the temperature required for BEC, using the technique of evaporative cooling. This technique had come out of the
magnetic field to confine the atoms in a way that made the evaporative cooling work much better and was the last step needed to reach BEC.

The actual apparatus we used to first make BEC is surprisingly simple. As shown in Fig. 1, the heart of it is a vapour cell MOT surrounded by additional magnetic trap coils. In an actual experimental run, we go through a series of steps. First the optical trap is turned on to collect atoms, second the sample of trapped atoms is optically cooled and compressed, and third the light is turned off and the magnetic trapping fields are turned on. Then the sample is evaporatively cooled.

![Diagram of BEC apparatus](image)

**Fig. 1.** 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.

To observe the sample we first turn off the magnetic fields, allowing the atoms to fly apart. We then take a ‘shadow snapshot’ of the expanded cloud. This shadow image gives the two-dimensional projection of the distribution of the speeds of the atoms in the original cloud in the magnetic trap. This is much like determining the speeds of the horses in a herd by starting them out in a small pen (the magnetic trap), then suddenly knocking down all the fences so the horses can run free. After a short time, one then takes a picture of the field to see the location of each horse. The faster horses have gone farther and are at the edges of the field while the slow horses are still bunched together close to the centre. From this one picture one can tell the average speed of the entire herd. In the same manner, we determine the average speed, and thus the temperature, of our previously trapped atomic sample.

A set of three such pictures corresponding to different temperatures are shown in Fig. 2! In the left-most picture, we have only cooled the atoms down to 400 nK (400 billionths of a degree above absolute zero) and what we see is a round hill which looks like the familiar velocity distribution observed in any normal gas. The middle picture shows a cloud of about 10,000 atoms that has been cooled to about 200 nK. On top of the rounded hill, a narrow spire, corresponding to a large number of atoms very close together, has emerged which is centred at zero velocity. If we cool even further (right), we can produce,
the atoms are combining to behave as a gigantic quantum wave and the detailed shape, including the elliptical character, arises from the Heisenberg uncertainty principle of quantum mechanics.

In the year and a half since we produced the first BEC, Hulet's group at Rice has found evidence for small condensates in lithium\textsuperscript{10} and Ketterle's group at MIT has convincingly demonstrated large (10\textsuperscript{7} atoms) condensates of atomic sodium\textsuperscript{11}. We have built a new apparatus\textsuperscript{12} that produces much larger condensates than our original and has a much greater margin of error in the operating conditions. This apparatus uses the same basic principle but it has two separate optical traps connected by a narrow tube. After the atoms are trapped in the upper chamber they are given a small push which sends them down the tube to be caught in the lower trap. The atoms will stay in the lower trap for many hundreds of seconds and so we can load many such bunches of atoms into it and thereby start out with many more optically trapped atoms. We then magnetically trap these atoms and evaporatively cool them to achieve condensates containing a few million atoms, about 1,000 times more than our original BEC samples.

These past 18 months have seen a burst of activity in the field of BEC. Over 150 theoretical papers on BEC have been submitted to journals from groups worldwide. In addition, there has been a substantial number of experiments performed both at MIT\textsuperscript{13} and at JILA\textsuperscript{12,14} to characterize the nature of the condensed gas. At least ten other experimental groups are close to being able to generate condensates as well.

To date, these preliminary studies have been fulfilling the expectations we had for BEC back when we first got involved in the field. For example, the strong parallels between BEC in a gas and superfluidity in liquid helium, noted at the beginning of this article, have been the motivation for some preliminary experiments looking at the low-lying excitations (vibrational oscillations) of the condensate. The oscillations of the condensate are akin to the quivering of a water balloon when it is poked. (The frequencies of these elementary excitations are intimately connected with the mechanism of superfluidity.) It turns out that theorists can very accurately predict the experimentally observed oscillation frequencies based on an independent knowledge of the interaction of two independent atoms. Making the corresponding connection in liquid helium is not possible. The particular frequencies of the oscillations are not as important as the ability to make the experiment-theory connection. This strongly suggests that with further experimental and theoretical work focused on how quickly the oscillations disappear, for the first time ever it will be possible to have a truly microscopic theoretical understanding of the mysterious phenomenon of superfluidity.

The connection between BEC and superfluidity was one of the suggestive analogies that originally enticed us into the field of BEC. A second compelling analogy was the connection between BEC and lasers—both are examples of macroscopic occupation of a single state. As it has turned out, within the last few months, experiments\textsuperscript{15} have confirmed that BEC and lasers indeed share the property of 'coherence', a discovery which may eventually lead to some of the most important applications of BEC.

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