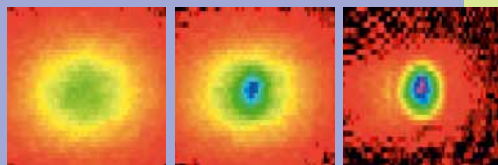


Bose-Einstein condensates

*Ultra-cold groups of atoms
that act as single wave-like
entities offer a new path into
the quantum world*



A decade ago, physicists created a new kind of atomic matter called a Bose-Einstein condensate (BEC). The phenomenon is not only providing new insights into quantum theory – which underpins our understanding of the Universe at the microscopic level – but also opens the door to a host of applications such as atom lasers, improved atomic clocks and quantum computers.

Quantum theory is a mathematical framework which describes the wave-like behaviour of atoms (as well as photons of light). Eighty years ago, Albert Einstein and the Indian physicist Satyendra Nath Bose predicted that a cloud of identical atoms would reveal their quantum character in an

particles with spins having a whole-number value – now called bosons.

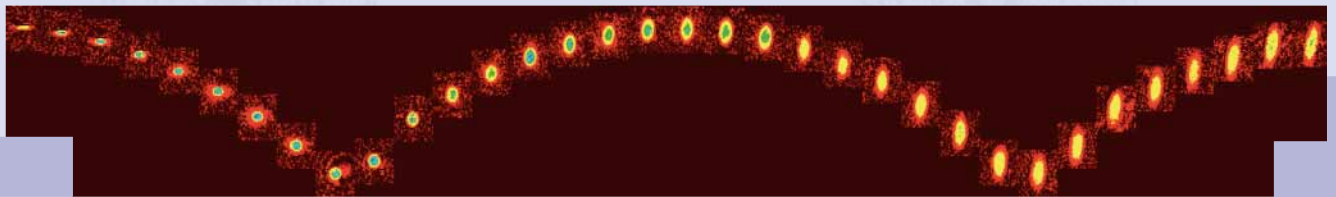
The first evidence for Bose-Einstein condensation was seen in liquid helium-4 in 1938. Below 2.12 kelvin, helium-4 atoms, which are bosons, form a fluid with no viscosity, or superfluid. Theorists believe that superfluidity is part of the BEC effect.

However, no-one had observed a BEC in atomic gases because it wasn't possible to cool them down to the required nanokelvin temperatures. Then in the 1980s, physicists began developing ingenious optical and magnetic techniques for isolating and trapping atoms, and slowing down their motions to a practical standstill. Alkali-metal atoms were ideal BEC

awarded the Nobel Prize in 2001. During the past decade, activity in the field has exploded, with more than 50 research groups around the world now making BECs. They have been produced from all the alkali metals, hydrogen, helium and even the heavy metal ytterbium.

The technique is ingenious. The atoms are slowed down with laser beams so they can be caged in a magnetic trap; the fastest atoms are then released so that only the most sluggish and therefore coolest remain. Methods of confinement evolved quickly with new magnetic configurations developed that could capture and retain millions of atoms. More recently, all-optical traps consisting of a lattice of beams

A. Arnold/Strathclyde University
A rubidium BEC bouncing off a soft magnetic mirror



Making matter behave as waves

unusual way. When cooled to extremely low temperatures, they would sink to their lowest energy state. As each 'atom wave' stretched and overlapped, their separate identities would blur to form a single wave-like 'super-atom' – a BEC. This behaviour applies only to

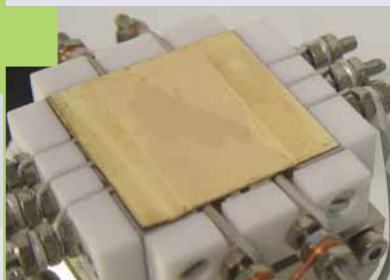
candidates to be cooled by these methods: their internal energies are easy to manipulate, and they are bosons. The race was on to create a BEC.

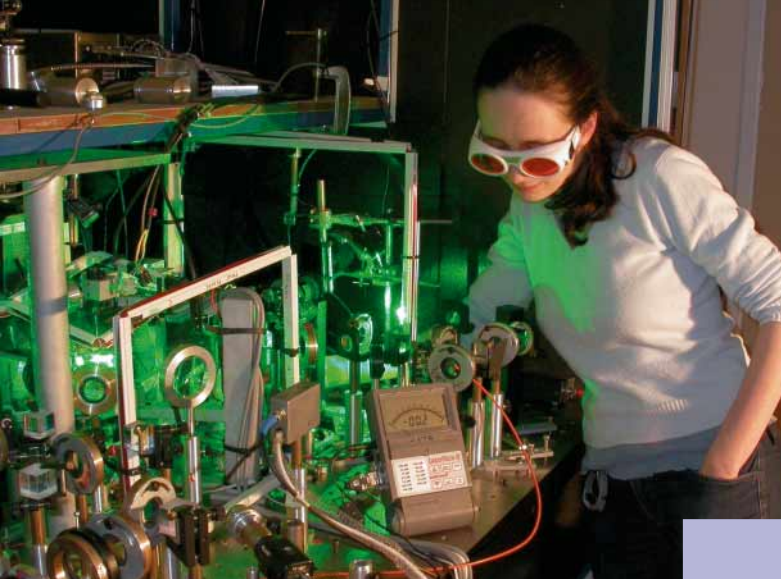
In June 1995, Eric Cornell, Carl Wiemann and their team at the JILA laboratory in Boulder, Colorado made the breakthrough. They cooled 2000 rubidium-87 atoms to less than 2 billionths of a kelvin, glimpsing the shadow of a BEC in a flash of laser light. Shortly afterwards, Wolfgang Ketterle and colleagues at the Massachusetts Institute of Technology created a sodium-23 condensate. They were all

produced by criss-crossed lasers have been employed.

Captured in such devices, BECs soon revealed their quantum wave-like behaviour. Ketterlee showed that two separate BECs could be combined to create an interference pattern, just as light waves do. BECs have been made to quiver like a jelly, 'ring' like a bell, and form minisunamis and smoke rings. They can be stirred up to form the persistent vortices tellingly characteristic of a superfluid.

A video chip used at Imperial College London to create a BEC





Making a BEC at Oxford University

beam. Immense effort has gone into developing approaches using magnetic fields, radiofrequency pulses and optical lasers, but these are extremely challenging experiments.

One promising 'real world' approach to creating BECs quickly involves using magnetic fields generated just above the surface of a microchip. Ed Hinds at Imperial College London has gone one step further, generating BECs in an array of magnetic traps on a videotape surface, and also in a glass-fibre guide. His aim is to develop a logic device for quantum computing.

Other UK researchers are also actively investigating BECs. Keith Burnett's group at Oxford University explores the many theoretical aspects of BECs, while Chris Foot and colleagues are working to cut out a regular array of ultracold atoms from a BEC squashed into a thin sheet, with the aim of producing a quantum version of analogue computing (where numerical data are represented by a changing physical quantity). Erling Riis and Aidan Arnold at Strathclyde University are developing a magnetic ring to store BECs for an atom interferometer.

Physicists are now in the throes of a revolution to manipulate this new state of matter in a wide variety of applications. We can expect exciting developments in the future.

Controlling cool atoms

One dramatic result arose from a crucial set of experiments to manipulate how the atoms interact. While rubidium-87 atoms form a stable BEC because they slightly repel each other, BECs of mutually attracting lithium-7 atoms tend to implode. However, judicious use of a magnetic field can change the repulsion to attraction. For example, a self-attracting rubidium-85 BEC can be made to be self-repelling so it swells; if the magnetic field is altered to make atoms attractive, the condensate shrinks and then suddenly explodes like a supernova (dubbed a bosonova) leaving behind a tiny core of atoms.

More recently, researchers have exploited this kind of manipulation to explore new territory in ultracold quantum gases. Some types of atoms have spins with a half-number value and are classified as quantum particles called fermions. These behave quite differently from bosons in that they always arrange themselves so that no two particles are in the same energy state. They would not be expected to form a BEC. Nevertheless, fermions can and do pair up into bosons – such composite particles, derived from electrons, are responsible for the related phenomenon of superconductivity.

In 2003, two research groups, one at JILA and one at the

University of Innsbruck, created molecular BECs of bosons, by pairing up fermion atoms of potassium-40 and lithium-6 respectively under the influence of a magnetic field. Such sophisticated experiments allow physicists to test quantum theory at its most fundamental level.

Applications

Meanwhile, many research groups have been exploring how to exploit BECs. Since an atomic BEC is a coherent wave, just like laser light, an 'atom laser' becomes a possibility. Such a device could be exploited in a similar way to optical lasers to create a new field of 'atom optics'. Atom lasers could be used holographically to 'paint' integrated circuits at the nano scale, while interferometers based on atom lasers could provide a new method of making precision measurements.

A working atom laser is still a way off yet. It requires an efficient method of releasing the BEC, while also replenishing the cold atoms and amplifying their number to provide a continuous

BECS IN THE UNIVERSE

Bose-Einstein condensation is a fundamental phenomenon of Nature. It is thought to have played a part in the evolution of the early Universe when the particles and forces formed, and the outer layers of a neutron star may well consist of a BEC of exotic subatomic particles. The properties of some advanced electronic and magnetic materials being explored today are mediated by composite bosons with quantum characteristics related to BEC behaviour.

Computer image of a neutron star

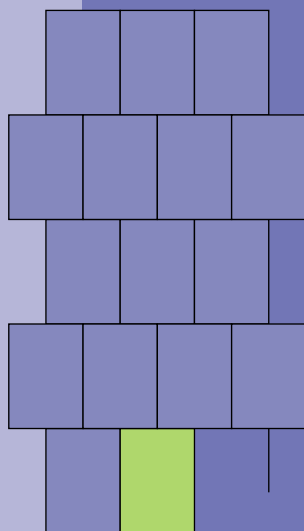


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Department of Higher Education and Research
The Institute of Physics
76 Portland Place, London W1B 1NT, UK
e-mail: tajinder.panesor@iop.org
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Further information about BECs can be obtained from the following websites:

<http://jilawwww.colorado.edu/bec>

www.imperial.ac.uk/research/ccm/research/coldatom1.htm

www.photonics.phys.strath.ac.uk/Research/AtomOptics/BEC.html