A New Form of Matter

Scientists have created a new kind of matter: It comes in waves and bridges the gap between the everyday world of humans and the micro-domain of quantum physics.

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March 20, 2002: It's not often that you get to be around for the birth of a new kind of matter, but when you do, the excitement is tremendous.

"To see something which nobody else has seen before is thrilling and deeply satisfying. Those are the moments when you want to be a scientist," says Wolfgang Ketterle, a physicist at MIT and one of the first scientists to create a new kind of matter called Bose-Einstein condensates.

Bose-Einstein condensates ("BECs" for short) aren't like the solids, liquids and gases that we learned about in school. They are not vaporous, not hard, not fluid. Indeed, there are no ordinary words to describe them because they come from another world -- the world of quantum mechanics.

Quantum mechanics describes the bizarre rules of light and matter on atomic scales. In that realm, matter can be in two places at once; objects behave as both particles and waves (a strange duality described by Schrodinger's wave equation); and nothing is certain: the quantum world runs on probability.

Although quantum rules are counter-intuitive, they underlie the macroscopic reality we experience day-to-day. Bose-Einstein condensates are curious objects that bridge the gap between those two realms. They obey the laws of the small even as they intrude on the big.

Below: BECs form when the atoms in a gas undergo a transition from behaving like the "flying billiard balls" of classical physics to behaving as one giant matter-wave. Image courtesy MIT.
A BEC is a group of a few million atoms that merge to make a single matter-wave about a millimeter or so across. In 1995, Ketterle created BECs in his lab by cooling a gas made of sodium atoms to a few hundred billionths of a degree above absolute zero -- more than a million times cooler than interstellar space! At such low temperatures the atoms became more like waves than particles. Held together by laser beams and magnetic traps, the atoms overlapped and formed a single giant (by atomic standards) matter wave.

Says Ketterle: "Pictures of BECs can be regarded as photographs of wave functions" -- that is, solutions to Schrodinger's equation.

Working independently in 1995, Eric Cornell (National Institute of Standards & Technology) and Carl Wieman (University of Colorado) also created BECs; theirs were made of super-cold rubidium atoms. Cornell and Wieman shared the 2001 Nobel Prize with Ketterle "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates."

Bose-Einstein condensates were predicted by Indian physicist Satyendra Nath Bose and Albert Einstein in the 1920's when quantum mechanics was still new. Einstein wondered if BECs were too strange to be real even though he himself had thought of them.

Now we know Bose-Einstein condensates are real. And Einstein was right: they are strange.

For example, notes Ketterle, if you create two BECs and put them together, they don't mix like an ordinary gas or bounce apart like two solids might. Where the two BECs overlap, they "interfere" like waves: thin, parallel layers of matter are separated by thin layers of empty space. The pattern forms because the two waves add wherever their crests coincide and cancel where a crest meets a trough -- so-called "constructive" and "destructive" interference, respectively. The effect is reminiscent of overlapping waves from two stones thrown into a pond.

Above: A picture of overlapping Bose-Einstein condensates. These shadows reveal an "interference pattern" -- a tell-tale sign of wave behavior. Image courtesy MIT.

"That means ... we have the remarkable effect that an atom (in one BEC) plus an atom (in another BEC) gives no atom. It's destructive interference," says Ketterle. "Of course we didn't destroy matter, it just appeared somewhere else in the pattern, so the total number of atoms is conserved."
Not all atoms can form Bose-Einstein condensates -- "only those that contain even numbers of neutrons plus protons plus electrons," says Ketterle. Ketterle made his BECs from sodium atoms. If you add the number of neutrons, protons and electrons in an ordinary sodium atom, the answer is 34 -- an even number suitable for Bose-Einstein condensation. Atoms or isotopes of atoms with odd sums can't form BECs. Strange, but true.


One of the most extraordinary aspects of Bose-Einstein condensates is that they are quantum creatures big enough to see. And there lies much of their promise. Many of today's cutting-edge technologies -- smaller, faster computer chips, micro-electro-mechanical systems (MEMS) and quantum computers -- lie in the twilight zone between the quantum world and the macroscopic world. Scientists hope that studying BECs will advance those technologies and create others.

Ketterle is already experimenting with one: a pulsed atom-laser.

"In an ordinary gas, atoms move around randomly, they flit around in all directions. But in a BEC, all the atoms march lock-step," Ketterle explains. "They are just one single matter-wave propagating in one direction."

Atom-lasers are akin to light-lasers, which are beams of photons that likewise "march lock-step." But there are differences: For instance, atom-laser beams have mass so they will bend downward in Earth's gravitational field. Light-laser beams are massless; they bend, too, but the effect is very small. Furthermore, light-lasers pass through air with ease. Atom-laser beams will be substantially scattered by air molecules.

Left: Atom-laser pulses produced in Ketterle's lab. The curved shape of the pulses was caused by gravity and forces between the atoms. [more]

"Atom lasers need a vacuum to retain their properties," notes Ketterle. As a result they won't be used in the same way as light-lasers. They won't improve CD players or supermarket scanners, for instance. But atom-lasers will doubtless find uses of their own -- "like better atomic clocks [which will improve spacecraft navigation -- a boon to NASA], atomic optics or very fine lithography," says Ketterle.

Who knows where BECs will lead? After all, humans evolved on this planet with solids, liquids and gases all around, and we're still figuring out innovative uses for them. With Bose-Einstein condensates ... we're just getting started.

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Editor's Note: Ketterle's ongoing research is supported in part by NASA along with other agencies.
A New Form of Matter -- an on-line lecture by Ketterle introducing and explaining Bose-Einstein condensates. (Highly recommended.)

This work was supported in part by NASA's Office of Biological and Physical Research.

The 2001 Nobel Prize in Physics -- awarded to the lead scientists for the two groups who first created Bose-Einstein condensates.

Illustrated presentation about BECs -- from the Nobel e-Museum Web site

Wolfgang Ketterle's Group at MIT -- home page

Questions and Answers about BECs -- from the University of Colorado

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