CORE CONCEPTS

How Bose–Einstein condensates keep revealing weird physics

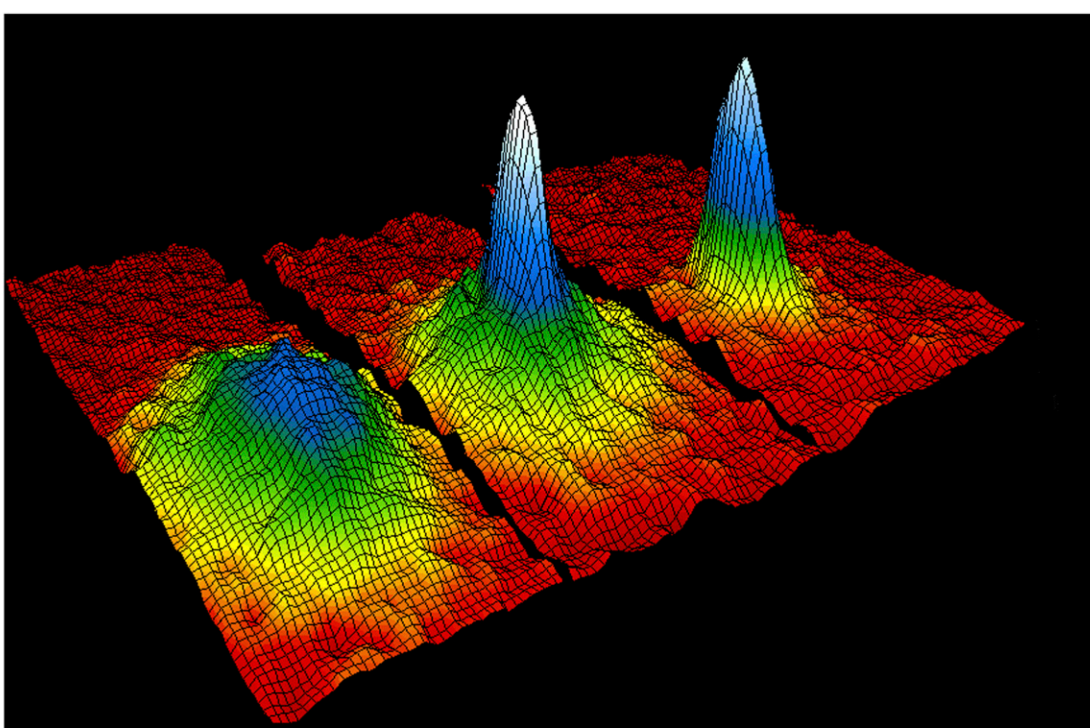
Stephen Ornes, *Science Writer*

A Bose-Einstein condensate (BEC), the first of which was shown experimentally 22 years ago, isn't your garden variety state of matter. It formed at a fraction above absolute zero and only in atoms that act like bosons, one of two types of fundamental particles. Bosons don't follow the Pauli exclusion principle, which prohibits two particles from existing in the same quantum state. When bosonic atoms are cooled to form a condensate, they can lose their individuality. They behave like one big collective superatom, analogous to how photons become indistinguishable in a laser beam. But it's even weirder than that.

"In a very good analogy, one can view a BEC as a bell, which begins to ring spontaneously when it is cooled below a certain temperature," writes physicist Nick Proukakis at the Joint Quantum Centre Durham–Newcastle in the United Kingdom, in *Universal Themes of Bose–Einstein Condensation*, a forthcoming collection of research essays on progress in BECs (1). That behavior provides physicists with an extraordinary opportunity: to study bizarre quantum effects on a large scale, instead of having to probe individual particles.

For the last two decades, physicists have treated BECs something like Play-Doh. They poke it, smash it, tickle it with lasers, and trap it in magnetic fields. They mix condensates together to see what happens, and use it to slow down light (2). They have observed strange behaviors that would have been impossible to predict even two decades ago: solids that flow through themselves, for example (3).

Scientists have made other surprising observations, like magnetic liquid droplets that fall like solid rocks, or neutral particles that act like they carry a charge (4, 5). Under certain conditions, BECs can be controlled to form swirling vortices, or explode like



This velocity-distribution data for a gas of rubidium atoms confirmed the discovery of the Bose–Einstein condensate in 1995. In these three snapshots in time, atoms—cooled to near absolute zero—condensed from less dense areas on the left (red, yellow, and green) to very dense areas at the center and the right (blue and white). Image courtesy of NIST/JILA/CU-Boulder.

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tiny supernovas (nicknamed "bosenovas") (6). As part of cutting-edge experiments, researchers are studying BEC in one or two dimensions, or using them to search for entangled atoms.

After the first observation in 1995, BECs ignited the field of cold atom physics. Some experts at the time denounced BEC research as a fad, an intellectual one-hit wonder that was interesting to witness but wouldn't significantly change the field. Now, experts working in the field today say it's just hitting its stride.

Ahead of Their Time

To create a BEC, physicists have to cool a diffuse gas of atoms—rubidium, in that first successful experiment—to within a few millionths of a Kelvin above absolute zero. That's no easy task, and researchers typically rely on two techniques. The first technique is laser cooling, which involves streaming lasers from six directions into the gas. An atom moving toward a laser absorbs a photon and slows down. Then it releases a photon in random direction. Over many repetitions of absorption and emission, the process reduces the speed of the atoms, and therefore the temperature.

The second method involves skimming off the warmest atoms; it's called evaporative cooling. During this stage, a magnetic trap holds the atoms and higher-energy atoms are allowed to escape, lowering the overall energy, and therefore temperature, of the sample.

"There's not enough time to explore all the interesting things the system can reveal," says Sandro Stringari, a theoretical physicist at the University of Trento, in Italy, who studies superfluids in BECs and other materials. Superfluids are a phase of matter with zero viscosity and zero entropy, which means they do surprising things, such as climb the sides of vessels where they're held. Superfluid behavior has long been associated with BECs, and Stringari's research is teasing out where one starts and the other begins. "I don't think everything has been probed yet," says Proukakis. "There are a lot of frontiers."

BECs were born from a letter. In 1924, Indian physicist Satyendra Nath Bose wrote to Albert Einstein, sharing his insights about an existing physical law describing how light and matter interact. "Though a complete stranger to you, I do not feel any hesitation in making such a request," Bose wrote. "We are all your pupils though profiting only by your teachings through your writings" (7).

In his letter, Bose challenged the derivation of the law, which used traditional statistical methods to describe the behavior of distinct particles. But light is carried by photons, which can be described as particles or waves. Bose described a new approach to analyzing particles like photons. Inspired, Einstein helped get Bose's work published. Their collaboration led to a new tool—Bose–Einstein statistics—and the prediction of new materials, Bose–Einstein condensates.

Making the stuff, as it turned out, would take decades. That's mostly because of the difficulty of achieving such low temperatures. In 1937, physicists discovered superfluidity in an isotope of helium cooled to 2.2 Kelvin, and many physicists argued that at least part of a superfluid consisted of BECs (8). But others remained skeptical, and the debate continued. At a 1993 meeting on the state of BEC research, some physicists even argued that quantum condensates were effectively impossible to make; that even though theory supported their existence, the state would need infinite time to form.

The first unequivocal demonstration of a BEC emerged 2 years after that meeting, in 1995, from physicists Carl Wieman and Eric Cornell at JILA (formerly known as the Joint Institute for Laboratory Astrophysics), a research institute at the University of Colorado, Boulder (9). The first BEC comprised a gas of rubidium atoms. "That opened a new field in quantum physics," says Stringari. Within a few months, physicist Wolfgang Ketterle, at the Massachusetts Institute of Technology, led the achievement of BEC in sodium. In 2001, Wieman, Cornell, and Ketterle shared the Nobel prize in physics for their groundbreaking work.

More condensates followed. In 1998 researchers produced a BEC in hydrogen. Since then, physicists have created BECs out of atoms of other metals, including lithium, potassium, cesium, calcium, strontium, chromium, and ytterbium. They've also confirmed that superfluid helium-4 does have a BEC component, as was long hypothesized.

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Physicists continue to probe BECs, says Proukakis, because after decades of fine-tuning their methods, the experiments offer excellent control of the material, and making BECs requires equipment that can be bought without breaking a research laboratory's budget. The potential rewards are high: Creative experiments isolate the most interesting physics, showing new weirdness at the quantum scale. "You can manipulate them very well, experimentally, and isolate the most interesting physics," says Proukakis.

Unknown Unknowns

BECs may be most interesting because of what researchers don't yet know about them. They're not found naturally on Earth, but some speculate that the high-pressure conditions around neutron stars may give rise to BEC-like gases (1). High densities in that extreme environment may bring the particles so close together they act like condensates.

What's unusual about BECs is the close interplay between theory and experiments. "The field is really defined by what can be done experimentally," says Ketterle. "Experimentalists have been creative in how to create new systems and introduce new detection methods, and that has inspired theory." Findings from Ketterle's laboratory, published in March, report new evidence for supersolid behavior in a BEC (3). Supersolids have an orderly structure, like a crystal, but flow without friction, like a superfluid, leading to phenomena such as flowing through itself.

That's not to say that theory takes a back seat. Proukakis, at Newcastle, says theory and experimental capabilities work hand-in-hand, which is why the field has moved so quickly in the last two decades. Supersolids, for example, were first predicted more than 50 years ago, but scientists weren't able to observe them experimentally until they'd figured out how to manipulate BECs.

What makes that synergy possible, says Ketterle, is the fact that experiments are relatively fast and flexible. The lasers and magnetic fields used to prod and control the condensate can be modified by researchers.

In the last two decades, those tools have become more precise and stable, and easier to use, and those advances have allowed physicists to ask deeper questions about the material, whether probing superfluidity or quantum gravity.

Even so, Ketterle says experiments that really push the research forward remain tricky and technically challenging. "The experiments were bloody difficult then, and they are bloody difficult now," he says. Twenty years ago, Ketterle and his students would spend all day stabilizing laboratory equipment and all night studying the condensate. "Today, you push a button in the morning and have a BEC," he says. But, he adds, there are many more "bells and whistles," such as new lasers and magnets that take time and patience to calibrate.

All this makes BECs a field of physics, says Ketterle, where curiosity can still dominate usefulness or applicability. "It's nice," he adds, "to be in an area of science where this happens."

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