D. LEE

Some like it cold

In 1995, scientists created the first ultracold quantum gas and to their surprise launched a new scientific field. Ten years on and its chilly revelations are attracting a growing number of physicists. Karen Fox joins the party.

Birthday parties don’t get much cooler than this — a mountain-top get-together for researchers fascinated by ultracold matter. Last month, to mark the tenth anniversary of the creation of the first Bose–Einstein condensate, physicists met in Banff, Canada, to discuss ultracold atoms in the morning and ski in the afternoon. The air outside was cold and crisp, but inside the atmosphere was invitingly warm. The scene verged on the cosy. A Nobel prizewinner could be found sitting next to a gaggle of graduate students, and speakers were interrupted by good-natured questions. Indeed, Kathy Levin, a theorist from the University of Chicago, began her talk by saying: “There is a wonderful *esprit de corps* and camaraderie here — which one doesn’t see in all fields, and which I think is a secret of its success.”

Levin recently escaped from the notoriously combative field of high-temperature superconductivity, another branch of condensed-matter physics. But her transition is not unique. In the past two years, with research into high-temperature superconductors stalled, more and more condensed-matter physicists have begun studying cold atoms. One is Fei Zhou of the University of British Columbia, who chaired a session in Banff and says he has never looked back since making the switch 18 months ago. Until then, Zhou says that every year he’d find fewer colleagues at the condensed-matter symposia he attended. By contrast, the field of ultracold atoms has swelled to some 100 labs and counting. There is excitement, funding and, most importantly, the chance to do some fascinating new science.

The concept behind Bose–Einstein condensation is much older than this youthful exuberance would suggest. In 1924, Albert Einstein and Satyendra Nath Bose used quantum mechanics to describe what would happen to a cloud of gas atoms if they were made so cold they essentially stopped moving. Squeeze them and they would merge into a single entity, a giant superatom. Locked together, moving as one, this condensate of atoms would become a new phase of matter — different from solid, liquid or gas.

This idea remained no more than a thought experiment until 1938, when helium-4 was cooled to below 2.2 K and became a new kind of fluid that flows without friction — a ‘superfluid’. But supercooled helium is a liquid rather than a gas, and so is not considered a ‘true’ Bose–Einstein condensate (BEC). Back then, creating the much colder temperatures necessary to make a gaseous condensate seemed impossible.

Then, in 1995, two groups did it almost simultaneously. Eric Cornell of the National Institute of Standards and Technology (NIST) and Carl Wieman of the University of Colorado in Boulder cooled 2,000 rubidium atoms into one entity; and Wolfgang Ketterle, a physicist at the Massachusetts Institute of Technology, made a condensate from half-a-million sodium atoms. These feats were recognized with a physics Nobel prize in 2001, but no one had foreseen just how much they would inspire a new generation of physicists.

“The past ten years have just been an explosion,” says Ketterle, who was unable to make it to Banff. “There have been so many surprises. When we discovered the BEC we had a short list of what we thought would be important. What has been done by far exceeds our expectations — in even my boldest dreams I could not think of so many interesting studies.”

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Ketterle’s surprise is understandable. Early research focused on making BECs — always a painstaking exercise — from yet more, and different, atoms. Creation was an end in itself. But over the past five years, BEC physics has grown, not just in size but in ambition. Today, although some researchers continue to characterize BECs, others attempt to apply BEC physics to other fields, and yet others are exploring the relatively new area of condensates made from a class of fundamental particle known as fermions.

An early question was whether BECs, like helium, are superfluids. In theory, once a superfluid starts swirling it should continue forever. Cornell and Wieman[1] first created such everlasting vortices in 1999, and today most people accept that BECs are superfluids. At Harvard University, physicist Lene Hau[2] recently formed both vortices and ‘straight density waves’, which are akin to a sound wave, in the same BEC. She watched them collide and blossom into something like a spinning

Physicists met in Banff (left) for the birthday of the first BECs, created by (left to right) Carl Wieman, Wolfgang Ketterle and Eric Cornell.

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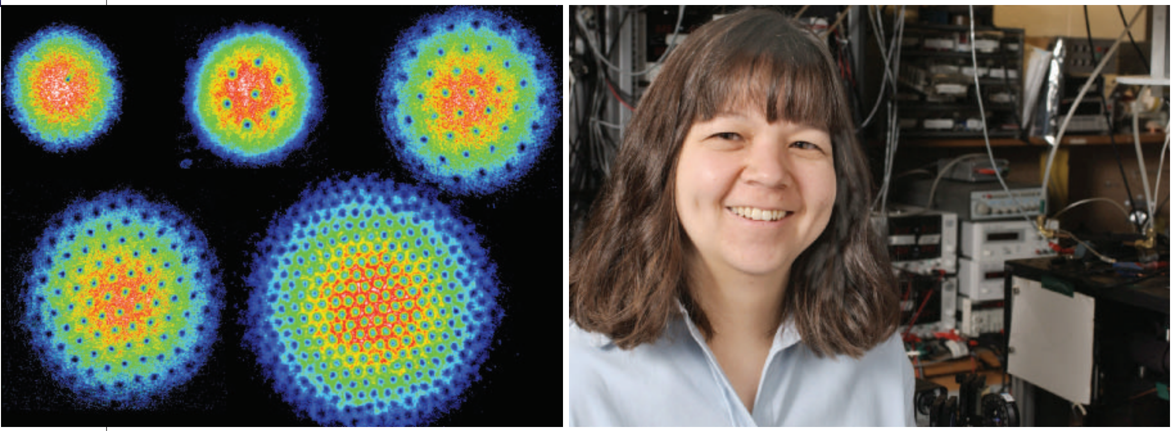

Young physicists like Debbie Jin drive a fast-moving field that has seen breakthroughs such as BEC vortex lattices (left).

A. GRIFFIN
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umbrella in the process of turning inside-out.

Such exquisite experiments demonstrate the control researchers now have over BECs. They have learned how to fine-tune the attraction between atoms in a BEC to do anything from spacing them in ordered lattices to forcing an entire BEC into something like a mini supernova. "I'm just amazed," says Ketterle, "that an experiment I thought was bloody difficult when I did it ten years ago is now being done regularly, with sophistication and much more experimental control."

And although theorists have had ten years to catch up, experiments are still driving the field. The moment a new theory comes out, there is someone in the wings ready to test it. "The experimentalists are wonderful," says Gordon Baym of the University of Illinois in Urbana–Champaign. "Not only do they do great experiments, but they do them once a week." It is this speed that helps make the field such a welcoming place. There is a sense that there is room for everyone.

Some of the fastest-moving research in cold atoms involves fermions. At a fundamental level, all matter comes in two varieties: fermions, such as protons, and bosons, such as photons. Creating condensates out of fermions instead of bosons was a highlight of the past two years. A star of fermion physics, Deborah Jin, a physicist with NIST in Boulder, discussed her latest work at the Banff meeting. As she describes it, one of the main differences between fermionic and bosonic matter is that two bosons can exist in the same place, like two crossing beams of light, whereas fermions cannot. This difference should rule out a fermion condensate.

But fermions can also behave strangely at low temperatures. When certain solids are cooled sufficiently, their conducting electrons — which are fermions — can pair up to create a boson, a phenomenon at the heart of our understanding of superconductivity. According to the 1957 Bardeen–Cooper–Schrieffer (BCS) theory, when two electrons merge to form a 'Cooper pair', this new boson can then effortlessly speed through the superconductor without resistance.

Early last year, Jin's lab reported a breakthrough — they had created bosons out of fermions and then turned them into a condensate[3]. From the start there were hopes that studying fermion condensates would give insight into BCS theory. This theory explains superconductivity only at very cold temperatures — high-temperature systems discovered in the 1980s spawned numerous theories and rancorous debate, but no firm explanations. It is perhaps this, more than anything, that has attracted so many condensed-matter physicists to the BEC field. As Randy Hulet, a physicist at Rice University in Houston, Texas, says: "We can use BECs to model condensed-matter systems so cleanly, in ways you just can't do in real condensed-matter systems."

Jin now hopes to 'see' a Cooper pair in a BEC — something researchers can only do indirectly in a superconductor. So far, the enigmatic dance partners remain hidden, but she can see correlations in the fermions' positions that hint at Cooper pairs. Although this work isn't conclusive, it offers hope that studying the links between BEC and BCS behaviour will deliver new insight. "BCS theory is just very robust within condensed matter," says Levin. "It is the theory of all theories — if it turns out to be part of an even bigger theory, which I believe it is, then that's very exciting for us."

Hulet, a veteran of cold-atom research, is also interested in how BECs can influence other fields. He was one of the first to create a BEC soliton, essentially a wave that never dissipates. These intense waves might one day be used to make inertial sensors for detecting changes in gravity or acceleration. Today's inertial sensing relies on optical instruments and Hulet believes that cold atoms could increase their accuracy. But he admits, "So far the solitons we can produce are too small."

The greater reliability of atomic systems compared with optical ones has even got the military interested. Major Jay Lowell at the US Defense Advanced Research Projects Agency (DARPA), which funds cold-atom research, says he would like to see inertial navigation systems based on BECs within five to ten years. DARPA's plans involve atom interferometer technology, pioneered by Ketterle's lab among others. An atom interferometer requires two coherent atom waves (essentially two atom lasers), which can then be made to overlap and produce an interference pattern.

DARPA is also tracking the potential of BECs in quantum computing — although Lowell's hopes for that are more in the 10–50 year range. Ignacio Cirac of the Max Planck Institute of Quantum Optics in Garching, Germany, gave a fascinating talk in Banff on how one might get BECs to behave as qubits — the basic building block of a quantum computer. For the moment, however, the idea remains firmly in the realms of theory.

Predicting which directions will bear more fruit — fermions, solitons or something unknown — is not easy, but a field that even insiders consider esoteric continues to generate excitement. Young physicists who were at graduate school when the first BECs were made are now claiming the field as their own, and many older scientists are switching to what they hope are greener pastures. Ten years on, there's no slowing down. "I thank my lucky stars," says Hulet, "that I stumbled on to this intellectual gold mine." ■

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