sate occupation to this upper level, and to study the collective excitations in such an unusual quantum fluid.

Wolfgang Ketterle (MIT) presented the results obtained with his improved apparatus, in which some 5×10^6 ^{23}Na atoms can be Bose condensed within a 30 s cooling time and in which the MIT group introduced the dark-field imaging method. An ingenious "clover leaf" coil geometry permits full optical access while offering the advantages of a Ioffe-Pritchard trap. The samples have a long, elongated shape so that the mean-free path in the axial direction can be made smaller than the sample size. This gives access to the hydrodynamic regime in which the free expansion of the gas is limited by the speed of sound. On collectively exciting the condensate, the normal mode frequencies were found to be in accordance with mean-field theory. As in the JILA experiments, the big issue here is to understand the damping.

Some of the most exciting aspects of the field at the present stage are of course the "simple" exploratory experiments. Ketterle mentioned several of them: cutting the condensate in two parts with a thin sheet of far detuned light and looking for interference fringes when the parts meet – the cutting works but the fringes are not (yet) observed. Then, addressing the quest for the atom laser, Ketterle showed how an RF pulse can be used as an output coupler to extract beams of (1,1) and (1,0) atoms from the condensate. Also here the search for coherence has still to begin.

W. Ketterle (MIT), on the right, with S. Chu (Stanford University) at EPS-10.

Some Definite Trends

What are the trends? Currently, all experiments are done with Ioffe quadrupole magnetic field geometries. This type of trap offers large flexibility in the choice of trap parameters such as minimum field, axial and radial frequencies, *etc.* Also, a good start has been made towards the ideal of accurate non-destructive detection, although there is room for improvement in spatial resolution, and for three-dimensional imaging. Looking at the future it is interesting to note that, thus far, the BEC phase line has only been crossed during cool-down by evaporation. Clearly, a next step will be to develop methods to cross the phase line reversibly. This would be a good starting point to investigate, for instance, the kinetics of Bose condensate formation, something simply inconceivable with high-density condensed matter. Another deep issue to understand will be the damping of collective excitations of the condensate which cannot be understood on the level of mean-field theory.

From the condensed matter side, there is a desire to watch the nucleation of a vortex in a condensate. From the quantum optics side there is a strong push to couple a coherent beam of atoms out of the condensate, aiming for the atomic equivalent of the laser. Or better still, look at phase relations between two independently created condensates. On the theory side, as Franck Laloë discusses below, the quantum opticians confront settled opinions of condensed matter theorists. It will be interesting to watch what both communities will contribute to the understanding of these dilute little gas clouds of common interest.

Is Particle Number Conservation Broken Spontaneously in Bose Condensates ?

Franck Laloë from the Ecole Normale Superieur reports that a particularly lively discussion on the question of spontaneous symmetry breaking in Bose-Einstein condensates took place during an improvised session at a recent Les Houches workshop on *Collective effects in ultracold atomic gases* (the workshop was organized by Christophe Salomon and Yvan Castin and attended by about 80 physicists from all over the world).

One refreshing characteristic of the field of ultracold atomic gases is that it brings together different scientific communities: condensed matter physicists who have been familiar with superfluid systems and their various theoretical aspects for years, and specialists in atomic physics and quantum electronics who have been busy with various properties of dilute gases for a long time, while superfluidity is of course something new. These fields have different traditions and cultures, and very naturally the newcomers to superfluids tend to question some concepts which are well established in condensed matter physics. One of them, which indeed gave rise to lively discussions between different points of view at the recent Les Houches workshop, is spontaneous symmetry breaking of particle number conservation. On the one hand, some condensed matter physicists consider this idea as completely indispensable for understanding the essence of superfluidity, while on the other hand some atomic physicists say that they could count the number of atoms in their traps so that invoking a violation of particle number conservation is more akin to magic than good physical reasoning. As always, a continuum of intermediate opinions between the two extremes is possible.

Symmetry Breaking

Initially, the idea of spontaneous symmetry breaking was introduced in the 1960s by analogy with ferromagnetism [see, for instance, P.W. Anderson, *Basic notions of condensed matter physics* (Benjamin, 1984); or P. C. Hohenberg & P.C. Martin, *Annals of Physics* 34 (1965) 291]. In spin ferromagnetics, the spin Hamiltonian is perfectly isotropic (the Hamiltonian commutes with angular momentum) so that there seems to be no preferred direction in space for a macroscopic magnetization to appear. Still we know that, in practice, below the transition temperature, all ferromagnetic systems "choose a direction in space" in order to develop a macroscopic magnetization; rotation invariance is broken. For superfluids, the symmetry is no longer invariance under space rotation, but invariance under a change of the phase of the wave function. This is related to the commutation of the Hamiltonian with the total number of particles and corresponds to a different invariance group than rotation, but otherwise the basic idea is the same. The analogue to the magnetization is the mean value of the quantum field operator, often called a "macroscopic wave function"; the latter can have non-zero values only if the system is in a coherent superposition of states with different numbers of particles. Another similar physical phenomenon is the onset of oscillations in a laser going through threshold; although lasers are not physical systems at equilibrium, when the oscillation starts, the system also "chooses a phase" in a process which is also analogous to the appearance of the quantum phase of a superfluid.

Needless to say, everyone agrees that the analogy is profound at a mathematical level and that the idea of spontaneous symmetry breaking of particle conservation is useful technically (the two-component nature of the order parameter determines the critical exponents near the superfluid transition; the idea is also used for writing anomalous averages in Green functions, *etc.*). Indeed it has proved to be an useful and productive tool in condensed matter physics, and it is not exaggerated to say that now it is really part of the culture of the field. Some physicists even consider the notion of symmetry breaking as a new basic postulate of quantum statistical mechanics, at the same level as the Schrödinger equation itself or the definition of entropy, for instance.

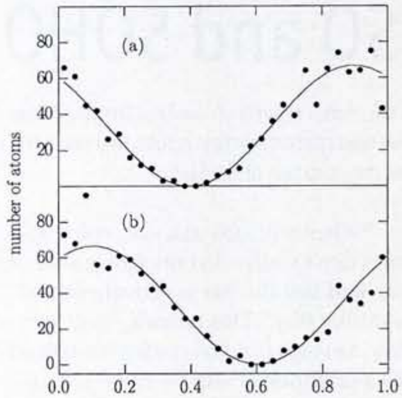
Not So Obvious

Why then question it ? In fact, it is not so obvious that ferromagnets and superfluids are so similar. For instance, when a magnet goes through the point of ferromagnetic transition, there is always a spurious magnetic field which will become able to determine the direction of the macroscopic magnetization. Because the magnetic susceptibility becomes infinite at the transition point, any non-zero magnetic field is sufficient. For the superfluid transition, mathematically the analogy is perfect: if one introduced by hand a little term in the Hamiltonian which creates particles (and therefore violate the particle conservation symmetry), this term would have little effect above transition, but a macroscopic effect below; in the same way, the "susceptibility" of the system to this perturbation also becomes infinite. But, physically, do these terms exist, even though no one has precise ideas to explain their physical origin ? Do they really create the coherent [1] superposition in question ? In short, is the analogy a real physical effect or just an elegant mathematical method for avoiding more complicated (but more realistic) calculations ?

At the 1993 Bose-Einstein conference organized by A. Griffin, D. Snoke and S. Stringari in Levico Terme (near Trento, Italy), A. Leggett had already treated the subject in a lecture entitled *On the uses and abuses of the notion of SBS (spontaneously broken symmetry)*. He emphasized that a macroscopic wave function in itself does not require non-conservation of particles and SBS, but can be introduced more simply in the spirit of Penrose and Onsager in 1956, just as the wave function of the state in which a finite proportion of particles starts to accumulate below the transition point. Nevertheless, when two superfluids can exchange particles by the tunnelling effect (Josephson junction), Leggett showed that this state is a always a coherent superposition of states located in the two subsystems (in the limit of very large systems), which reproduces the SBS results for the physical quantities of interest. Moreover, he discussed the possibility of an universal phase etalon allowing one to measure, by comparison, the phase of all superfluid baths [2] made and cooled down independently in different parts of the world.

A Radical View

At the Les Houches workshop, J. Javanainen took a more radical point of view, advocating that SBS was not at all an essential ingredient of the physics of interference between two Bose-Einstein condensates. In his talk, he considered a thought experiment where two non-interacting condensates are "dropped" on each other and where appropriate detectors detect the position of the particles during their overlap. Adapting the well-known theory of photon detection to this case, he was able to show numerically that beautiful interference effects take place when correlations between atomic positions are considered, even with no violation of particle number conservation whatsoever (see figure). While no one had the slightest doubt of the fact that the calculations were correct, contradictory points of view were expressed on their interpretation and their impact on the understanding of the Josephson effect, for instance. But, in a lively subsequent lecture, A. Griffin expressed different views and explained why any model that misses spontaneous symmetry breaking misses an essential ingredient of the physics of superfluidity. "I challenge theorists to explain superfluidity without a mean value of the field operator !" he said. Several other talks touched the same question, among them one by J. Dalibard, who considered a system of many atoms condensed into two different states interfering through an appropriate beam splitter. He showed how in repeated measurements the same results can be obtained either from an "atomic physics" point of view where particle number is explicitly conserved, or from another approach where the two subsystems are each put in a coherent state with violation of the particle conservation symmetry. All these questions can be, of course, transposed to superconductors, where the BCS Cooper pairs of electrons play the role of the bosonic atoms.



A numerical simulation of the outcome of the interference between two Bose-Einstein condensates when one is dropped onto the other. The points give the number of atoms falling within a bin at position x as a function of x. They were obtained by computing the probability distribution for detecting an atom using two different models (a and b) and then generating random samples from the distribution. Lines give least-squares fits assuming a distribution of the form $1+\alpha\cos(2\pi x+\varphi)$. It can be seen that the atoms display an interference pattern (bands of high and low atomic densities), as predicted by conventional reasoning using the phases of the macroscopic wave functions describing the condensates, even though the condensates were assumed to be number states with no phases. [J. Javanainen & S. M. Yoo, *Phys. Rev. Lett.* **76** (1996) 161].

So no complete consensus was reached among all participants on the question. Extensive future discussions of the subject will certainly take place. Whatever the outcome is, it is already clear that the new superfluid gases, with the flexibility that they offer since their densities can easily be varied by large factors (as opposed to liquids which have almost fixed density), will allow a whole variety of new experiments, including refined tests of the various theoretical approaches. Cross fertilization of different fields will be the result, as is so often the case in physics.

Notes

[1] The analogy with the grand canonical ensemble, which is sometimes invoked in this context, is not relevant: the question is not to include incoherent superpositions of different numbers of particles, but coherent superpositions allowing a phase.

[2] More precisely, all superfluids made of the same particles. One would need as many phase etalons as there are different kinds of superfluids (one per different alkali atom for instance), which is another difference with ferromagnetics where the directions of magnetization may be measured with respect to any frame in space and used as a reference for any other kind of ferromagnet.