distribution of He* atoms hitting the plate, from which the distribution of atoms along one direction could be inferred. To make room for the MCP below their condensate, the Orsay researchers used a cloverleaf design for their trap. The team observed condensation at about 0.7 μK, with up to about 10^5 atoms condensed. With the MCP, the Orsay group was able to study condensates containing as little as a few hundred atoms.

The ENS group used the more traditional technique, common for alkali condensates, of absorption imaging following free expansion with the trap turned off. Figure 2 shows sample images of the He* condensates. The ENS researchers observed the BEC transition at 4.7 μK, with a maximum of about 5×10^5 atoms in the condensate.

Both groups observe a lifetime of a few seconds for the He* condensates. It's still too early to tell the extent to which two-body Penning ionization collisions and three-body collisions contribute to the condensate decay rate.

New regimes, opportunities

A key parameter describing condensates is the s-wave scattering length, a, which characterizes the strength of the interactions between atoms. Both groups extracted values on the order of 20 nm for the scattering length in He*, although the uncertainties are still fairly big. That's about four times larger than rubidium's scattering length, and more than a hundred times greater than hydrogen's. The large value for a made evaporative cooling more efficient—a critical contributor to the experimental success.

The large value of a for He*, combined with the high density of atoms attainable in these condensates, should allow new regimes of condensate behavior to be probed. The ENS researchers reported that, near their BEC transition, the collision rate between He* atoms—given by the product of the density, the cross section (proportional to a^2), and the average thermal velocity (high in He* because of the light mass)—is much larger than the characteristic trap frequencies, placing the condensate in the hydrodynamic regime instead of the so-called collisionless regime studied so far in other condensates.

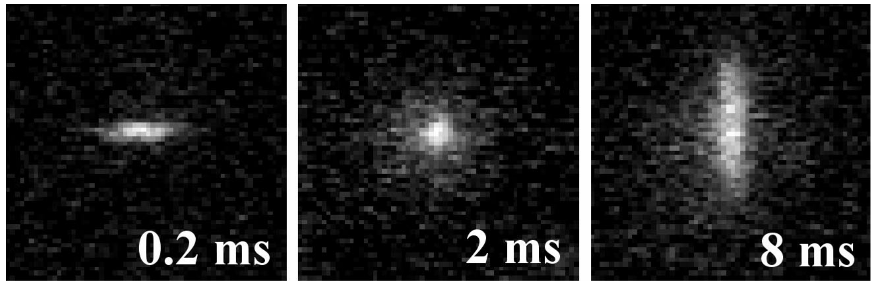

FIGURE 2. ABSORPTION IMAGES of a cloud of metastable helium atoms at Ecole Normale Supérieure, for various times of free expansion. The change in ellipticity is a telltale sign of Bose–Einstein condensation. (Adapted from ref. 2.)

Because of the frequent collisions between He* atoms, the condensate and the noncondensed atoms (the "thermal cloud") can be in local equilibrium with each other. In this situation, says Allan Griffin (University of Toronto), the system can be described by the two-fluid hydrodynamic equations developed by Lev Landau in 1941 to explain the superfluidity of liquid ^{4}He. For example, the analog of "second sound," in which the condensed and noncondensed components oscillate out of phase, should be observable in the He* condensate. In 1998, Wolfgang Ketterle's group at MIT reported the onset of hydrodynamic behavior in sodium condensates, but the He* condensates are the first to be well within this domain.

The large scattering length and high density in He* condensates have another implication: The scattering length can be a significant fraction of the distance between He* atoms. The ratio is on the order of several percent in these experiments, compared to less than 0.1% in the alkali condensates. With such a large ratio, He* condensates should show deviations from the simple mean-field theory that's been used to describe other condensates, notes Charles Clark (NIST Gaithersburg). Forays into this regime have been made by Carl Wieman, Eric Cornell, and colleagues at JILA by tuning the scattering length in ^{85}Rb condensates (see PHYSICS TODAY, August 2000, page 17).

MCP detection opens up new avenues of investigation, too. The Orsay researchers were able to analyze the background ionization recorded with their MCP to obtain real-time information about their condensate's formation and decay. Furthermore, the extremely high sensitivity of the MCP makes possible the study of small condensates far from the thermodynamic limit. The ability to prepare small samples of He* atoms and detect the atoms one at a time also creates new possibilities in quantum atom optics experiments, such as measurements of atom interference, coherence, and density correlations on an atom-by-atom basis.

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Dramatic Evidence Seen for Collective Behavior among Electrons in Closely Separated Layers

The Josephson effect is a dramatic macroscopic manifestation of quantum mechanics: If you separate two superconductors by a thin insulating barrier, a current can flow across the junction with no voltage applied. Similar behavior was recently seen in a system that involves neither superconductors nor superfluids. Experimenters from Caltech and Bell Labs, Lucent Technologies, formed two parallel layers of electrons, separated them by a very small distance, and measured the tunneling conductance between them, that is, the differential change in interlayer current with voltage.[1] As the voltage dropped to zero, the researchers saw an enormous peak in the conductance—much more than could be explained by ordinary tunneling. Such strongly enhanced conductance, shown in figure 1a, suggests that electrons in

Theorists describe the two-layer system as a Josephson junction, an exciton condensate, or a ferromagnet.

the two systems form a collective system much like a superfluid.

The electron layers were actually quantum Hall states, that is, two-dimensional electron gases in a high transverse magnetic field. The charges in each layer move in quantized cyclotron orbits about the magnetic flux lines, performing what Xiao-Gang Wen of MIT describes[2] as a "quantum dance of electrons." Over a decade ago, theorists began to realize that if two such quantum Hall states were brought close enough together, the electrons in the two layers would feel one another's presence and join in a coordinated dance.

The tunneling of electrons is usually strongly suppressed because it's very hard to squeeze an electron from one layer into the highly ordered pattern of the other. In the recent experiment, however, Ian Spielman and James Eisenstein of Caltech and Loren Pfeiffer and Ken West of Bell Labs found that when electrons were as close to those in the opposite layer as to those in their own layer, it would take only a tiny voltage to get a huge change in tunneling current. (The electron layers form in doped quantum wells in a gallium aluminum arsenide heterostructure. The distance between layers is fixed, but experimenters can control their effective separation with the magnetic field and gate voltages.)

Over the years, theorists have predicted that a quantum Hall bilayer would exhibit a number of exotic properties. Still, they were astonished to see the predicted collective behavior manifested in such a spectacular manner. Five groups of theorists published their take on the experiment in a single issue of *Physical Review Letters*.[3–7]

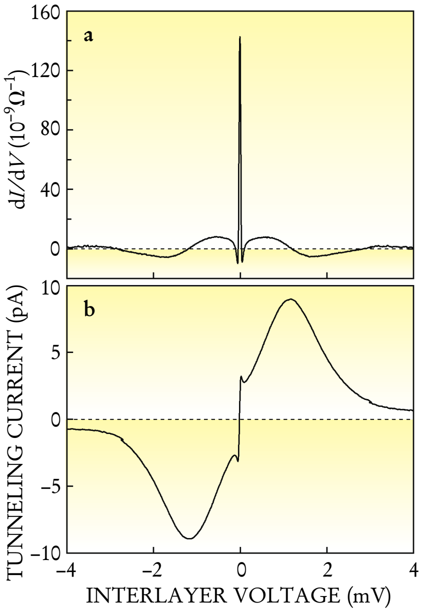

FIGURE 1. CURRENT–VOLTAGE characteristics of a quantum Hall bilayer. **(a)** The high peak in conductance (dI/dV) suggests that electrons behave collectively. **(b)** The current passes through zero very steeply, although it is not quite discontinuous, as it would be if it were a conventional Josephson junction. (Adapted from ref. 11.)

Which layer?

Figure 2, suggested by Steven Girvin (Indiana University), depicts the bilayers at relatively large (top) and small (bottom) separations. (See Girvin's article in PHYSICS TODAY, June 2000, page 39.) In the Caltech–Bell Labs experiment, the ratio of electrons to magnetic flux quanta, that is, the filling factor ν, is ½ in each layer. At large separation, each electron is associated with two magnetic flux quanta, and the electrons in the two layers act independently of one another. When the layer separation is small, interlayer interactions become important, and the two layers now behave as if they were a single layer in a $\nu = 1$ state, having each electron paired with a single flux quantum. Every electron stays away from the flux quanta associated with the other electrons, no matter what layer those electrons are in.

This collective state lowers the energy penalty for an electron to move between layers: In effect, each electron has a space reserved for it in the other layer. Thus, it's impossible to know in which layer an electron sits. You can describe such a system in terms of two complementary variables: the total number in the two layers ($N_1 + N_2$) and the imbalance between the two layers ($N_1 - N_2$). The first is precisely specified, and the latter becomes indeterminate.

In 1989, Herbert Fertig (University of Kentucky) described the microscopic quantum ground state for this system and predicted the existence of a zero-energy collective oscillation called a Goldstone mode.[8] In 1992, Wen and Anthony Zee (University of California, Santa Barbara) used different language to describe how the symmetry associated with conservation of $N_1 - N_2$ (in the absence of tunneling) could be broken.[9] They predicted the giant Josephson-like peak in the tunneling conductance. (Other theorists made closely related predictions.[10])

In the ground state of the broken $N_1 - N_2$ symmetry, each electron is in a linear superposition of the two layers, described by a phase angle ϕ. Every electron has the same value of this phase, and the symmetry is broken when the system spontaneously (but arbitrarily) picks a specific value of that phase. The smallest excitation of this ground state consists of a very slow change of the phase from one electron to the next, and that excitation is the Goldstone mode. It's a very long wavelength excitation; the changes occur so gradually that its energy is virtually zero.

In a superfluid, the gradient of the phase is the superfluid velocity. Hence, the Goldstone mode is associated with an oscillation in the electron density of the bilayer: The electrons in the two layers move back and forth out of phase with one another.

To show that a Goldstone mode is present in the quantum Hall bilayers, one needs to measure the dispersion curve for such an excitation, that is, how the energy of the mode varies with momentum. In a recent experiment,[11] Eisenstein and his collaborators excited the Goldstone mode with a given momentum by applying a magnetic field parallel to the electron layers. The Lorentz force gives extra momentum to the electrons as they tunnel, and that momentum goes into creating the Goldstone excitation. Applying the field splits the zero-bias conductance peak, and the voltage at which the two side peaks appear gives the energy of the Goldstone mode. The dispersion curve thus determined by the Caltech–Bell Labs group was linear, as predicted, although its details are not in full agreement with calculations.

Various interpretations

Theorists have come up with different ways to picture the quantum Hall bilayer, although these pictures are all formally equivalent. Some theorists describe the combined quantum Hall state in the language of magnetism. They define a pseudospin vector that points up if the electron is in layer 1 and down if it is in layer 2. When the electrons might be in either layer, the system is described as a linear combination of the up and down vectors. The result is a vector lying in the xy plane in pseudospin space whose orientation is determined by the phase angle ϕ already introduced. In the pseudospin picture, the system has the symmetry of a two-dimensional ferromagnet, with all spins aligned in an arbitrary direction.

In another view, an electron in one layer is attracted to a hole in the other layer, and the pair forms an exciton that spans the junction. The polarization of each exciton is unknown because one can't tell where the electron is. The collective state is then a condensate of these excitons, which behaves as a superfluid.

A third picture, which further develops the excitonic description, is that of the DC Josephson effect. As presented by one pair of theorists, the excitonic condensate of the quantum Hall bilayer is governed by the same equations as the Josephson junction, with ϕ playing the role of the phase difference between superconductors.[5] In the views of these theorists, the excitonic condensate embodies the essence of the Josephson effect: It's a coherent system with an indeterminate number of excitations carrying charge in each layer.

Nagging questions

As tempting as it is to make a complete analogy with the Josephson effect, the Caltech–Bell Labs experiment does not yet fit in all regards. In particular, at zero voltage the experimenters observe zero current, not the finite supercurrent one expects from a Josephson junction (see figure 1b). According to Eisenstein, it is not yet clear whether the zero current is intrinsic to the way tunneling works at $\nu = 1$, or is caused by some unknown extrinsic experimental effect. The slope of the I–V curve near $V = 0$ keeps getting steeper (and the associated conductance peak taller and sharper) as he and his team improve the experiment. So, Eisenstein believes, the jury is still out on whether they have a Josephson junction.

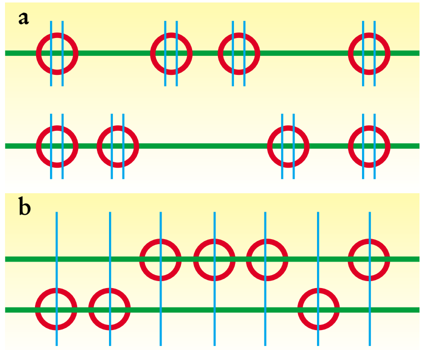

Figure 2. Quantum Hall bilayers are depicted by electrons (red circles) associated with magnetic flux quanta (blue lines). **(a)** At large separation, each electron is associated with two flux quanta and is little influenced by electrons in the other layer. **(b)** At small separations, the electrons move in a collective state, each associated with a single flux quantum and each keeping its distance from the others.

Sankar Das Sarma of the University of Maryland, College Park, believes the evidence for a collective mode in the quantum Hall bilayer, but does not think we can claim a full understanding of it until we can reproduce its quantitative as well as qualitative features. To that end, two groups recently tried to understand in detail the observed height and width of the zero-conductance peak in the Caltech–Bell Labs experiment.[3,4] They examined the role of disorder in this system. At the same time, Das Sarma and two colleagues explored the possible ground states of the quantum Hall bilayer and found a large number of them, including some that exhibit only a quantum Hall effect or coherent electrons.[7] In yet other work, a group from Indiana University examined the evolution of the bilayer system between the extremes of large and small separation.[6]

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Novel B Factories Close in on the Violation of *CP* Symmetry

How well does *CP* violation obey standard particle theory? Electron–positron colliders of a new kind were built in the US and Japan to find out.

It's been two years since PEPII and KEKB, two "asymmetric B factories," one on either side of the Pacific, began their competing assaults on the important problem of *CP* symmetry violation in particle physics. And now we have the first substantial results.[1,2]

Both PEPII at SLAC and KEKB at KEK, the high-energy accelerator laboratory in Tsukuba, Japan, are electron–positron storage-ring colliders. Their novel asymmetric feature is that the two countercirculating beams in each machine don't have the same energy: An 8- or 9-GeV electron beam collides with a lower-energy positron beam to produce B-meson pairs in abundance, in a configuration that greatly facilitates the examination of *CP* violation in the decays of neutral B mesons. The charged and neutral B mesons, about five times more massive than the proton, carry the heavy third-generation bottom quark (b) or its antiquark ($\bar{\mathrm{b}}$).

Though both machines are performing brilliantly at this early stage, neither has as yet produced conclusive evidence for *CP* violation in B decay. The only clear evidence we have for the violation of *CP* symmetry in nature—aside from the cosmic preponderance of matter over antimatter—comes from the decay of neutral K mesons. *CP* denotes the combined operation of charge conjugation (*C*), the replacement of particles by their antiparticles, and parity inversion (*P*). After the rude overthrow of parity conservation in 1957, *CP* offered a refuge for believers in mirror symmetry, but only until 1964, when *CP* violation was discovered in a small fraction of K^0 decays.

What spoils the symmetry?

Why all this effort to study *CP* violation by neutral B mesons? In 1973, before there was any hint of the third generation of quarks (the bottom and top, t), Makoto Kobayashi and Toshihide Maskawa made the prescient observation that, within the standard model of particle theory, a third quark generation would provide a natural mechanism for *CP* violation. But, after decades of painstaking K-decay experiments, we still don't know whether the Kobayashi–Maskawa mechanism is the principal source of *CP* violation in particle physics (see Physics Today, May 1999, page 17). The question is important, because particle physicists are urgently seeking evidence of any