The ^{3}He Superfluids

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The ^{3}He Superfluids

The curious properties of this millikelvin liquid show quantum mechanics operating on a macroscopic scale. At nanokelvin temperatures even more bizarre liquids may exist

by Olli V. Lounasmaa and George Pickett

The intensely hot conditions that prevailed at the universe's birth probably lie forever beyond the reach of even the largest particle accelerators. Investigators of low-temperature physics, however, have long surpassed nature. In the 15 billion years since the big bang, no point in the universe at large has reached a temperature cooler than three kelvins (the temperature of the cosmic microwave background). In laboratories, however, temperatures measured in nanokelvins and picokelvins are being achieved. The phenomena being studied at such temperatures are not only new to physicists, they have never occurred before in the history of the cosmos.

Of all the unusual phenomena that ultralow temperatures elicit, perhaps the most spectacular are superfluidity—the frictionless flow of a fluid—and its electronic analogue, superconductivity. Superfluidity in liquid ^{4}He, the common isotope of helium, has been known since 1938. In 1972 Douglas D. Osheroff, Robert C. Richardson and David M. Lee of Cornell University found that the rare isotope ^{3}He could also become superfluid. Exploration of the properties of this new kind of matter has been a central project of ultralow-temperature physics for the past decade and a half.

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The behavior of superfluid ^{3}He can be very intricate even though its structure is that of a simple liquid, composed of identical, chemically inactive, rare gas atoms. In addition to being worthy of study for its own sake, this combination of the simple and the complex makes superfluid ^{3}He an ideal substance in which to study many other condensed-matter problems, ranging from the properties of neutron stars to those of high-temperature superconductors.

Helium at low temperatures is a "quantum liquid." That is to say, quantum mechanics plays an important role, not only in its microscopic properties but also in its macroscopic behavior. Helium's superfluid nature arises from the interplay of quantum mechanics, which imposes a fundamental minimum of uncertainty on the behavior of individual atoms, and the third law of thermodynamics, which requires a substance to become perfectly ordered as its temperature approaches absolute zero. At high temperatures, substances are gaseous, and their atoms fly about at random. As the temperature falls, a substance condenses into a liquid and ultimately freezes into a solid, in which the position of every atom should be fixed.

On the quantum side, Heisenberg's uncertainty principle states that a particle's momentum and position cannot both be precisely known at the same time; measuring one produces uncertainty in the other. Helium atoms are very light and interact only weakly; as a result, their positions are quite uncertain even at absolute zero. They cannot be kept stationary enough to form a solid at low pressures because of their large zero-point motion.

The result is something of a paradox: superfluid helium atoms remain liquid even at the lowest temperatures, but unlike ordinary liquids, whose fluid motion is a sign of internal disorder, low-temperature liquid helium is perfectly, though subtly, ordered.

The particular ordering that takes place in liquid helium is a consequence of a fundamental division that exists in quantum mechanics between fermions (named after Enrico Fermi) and bosons (named after Satyendra Nath Bose). Bosons comprise such force-carrying particles as photons and pions. Their spin is an integer multiple of the fundamental quantum of angular momentum, $\hbar$, Planck's constant divided by 2π. Any number of bosons can occupy the same quantum state simultaneously. This means that at absolute zero all the bosons in a given system can condense into a single lowest-energy quantum state.

Particles whose spin is a half-integer multiple (1/2, 3/2 and so on) of $\hbar$, such as electrons, protons and neutrons, are fermions. They are the particles from which matter is built. At any given time, only one fermion can occupy a particular quantum state; this rules out the condensation of all the particles to a single lowest level.

A ^{4}He atom consists of two electrons, two protons and two neutrons, each with half-integer spin. As a result, the atom is a boson. When ^{4}He is cooled below a critical temperature, called the lambda point (2.17 kelvins under zero pressure), the liquid starts condensing to the lowest-energy state. At very low temperatures, almost the entire liquid is in this state, and so a single quantum-mechanical wave function describes not just the behavior of individual particles but that of the whole macroscopic liquid.

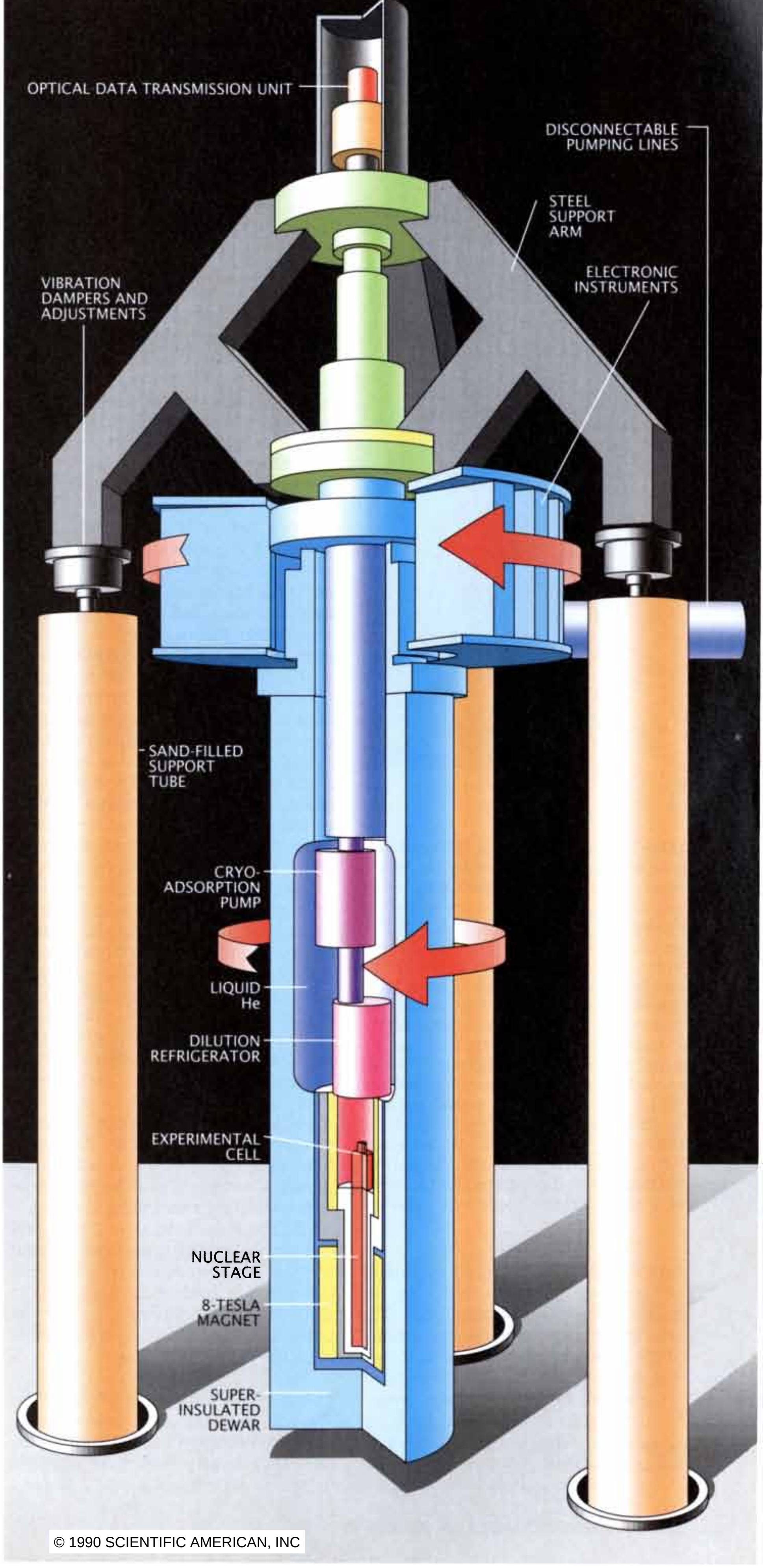
Furthermore, a significant amount of energy and momentum is required to promote the liquid into an excited state. This condition produces superfluidity. In a normal fluid, collisions between atoms or between atoms and the walls of a container can easily shift an atom from one energy state to another state of nearly equal energy and dissipate a fluid flow. Helium liquid in the ground state, however, cannot be shifted into a different state by low-velocity collisions. There is no mechanism for energy dissipation.

Superfluidity in ^3He has a somewhat different character. Its atoms contain an odd number of neutrons and so an odd number of particles in sum. Thus, they are fermions and are unable to condense into a common ground state. As a result, ^3He cannot become superfluid as easily as its boson sibling can. Instead, at a transition temperature roughly 1,000 times lower than that of ^4He, a weak attraction between ^3He atoms begins to make itself evident. Atoms with equal and opposite momenta tend to form pairs in which the two particles orbit each other at a distance. These pairs (called Cooper pairs after Leon N. Cooper, now at Brown University, who originally proposed an analogous pairing of electrons to explain superconductivity) are bosons—their half-integer angular momenta add up to an integer value. Therefore, they can condense to a common ground state and form a superfluid.

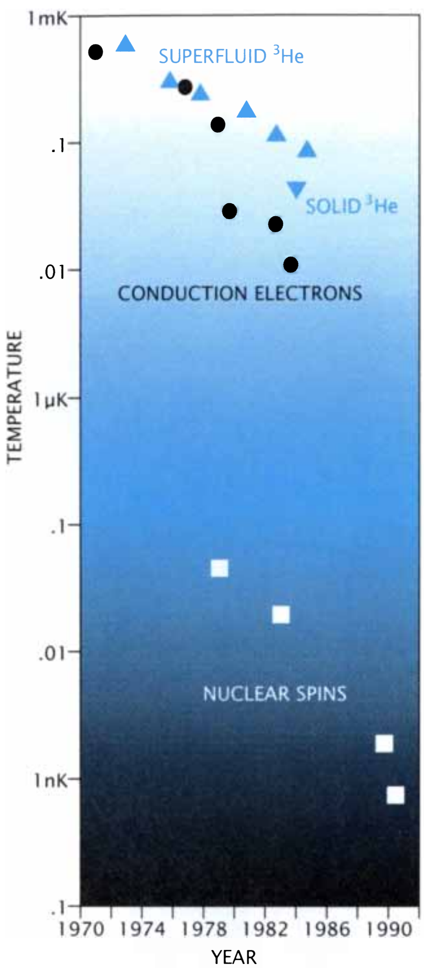
Indeed, they form two superfluids, ^3He-A and ^3He-B. In the A phase the nuclear spins of the two atoms tend to lie perpendicular to the axis of orbital motion, whereas in the B phase the correlation is more subtle.

Because all pairs of ^3He are in the same state, the relations between spin and orbital motion are associated not only with individual pairs but with the superfluid as a whole. Superfluid ^3He thus has directionality, rather like a liquid crystal; it can be aligned by external factors, such as magnetic fields, liquid flow or surfaces. The spatial arrangement of these directions in the liquid is known as the texture. (Atoms of ^4He have no spin and so no special directional properties; superfluid ^4He thus has no texture.)

The behavior of superfluids differs from that of conventional fluids not only in degree but in kind. One notable anomaly manifests itself if one tries to rotate a superfluid. A normal liquid in a bucket that is



ROTATING CRYOSTAT creates vortices in superfluid ^3He. The three-meter-high apparatus, located at the Helsinki University of Technology, can spin at rates as high as 30 revolutions per minute. It contains not only the liquid helium but also experimental sensors and a multistage cooling system.



LOW-TEMPERATURE RECORDS shown above have been attained in ^{3}He, which must be cooled by contact with other substances, in the electrons of metals cooled by magnetic ordering and in metal nuclei considered by themselves. The lowest temperatures in liquid ^{3}He (around 100 microkelvins) have been achieved at Lancaster. (Hidehiko Ishimoto's group at the University of Tokyo has brought solid ^{3}He to 43 microkelvins.) The Lancaster group has also cooled conduction electrons in copper to 12 microkelvins, a record equaled by Frank D. M. Pobell's group at the University of Bayreuth. In February Pertti J. Hakonen and Shi Yin in Helsinki lowered the nuclear temperature of a silver sample to 800 picokelvins.

spinning at a constant velocity rotates at the same angular velocity as the bucket, as if it were a solid body. The velocity, and thus also the momentum of the liquid, is proportional to the radial distance from the axis of rotation.

Superfluid helium, however, cannot be made to rotate as a solid body because of its status as a quantum liquid. Uniform rotation requires that the velocity, and consequently the momentum, of the liquid increase linearly with distance from the axis of rotation. Momentum and wavelength are inversely proportional to each other, and so the quantum wave functions of atoms in the outer part of the liquid must have shorter wavelengths than those of the atoms nearer the axis of rotation. That is perfectly possible for atoms in a normal liquid because each one has its own wave function. All the atoms in a sample of superfluid helium, however, are described by a single quantum-mechanical wave function, and it is geometrically impossible to construct a circular set of peaks and troughs whose spacing decreases with increasing radius. Superfluid helium exists in a state of nonrotation with respect to the universe as a whole.

What is possible is a wave function whose wavelength increases with increasing radius. Such a pattern corresponds to the motion of liquid around a whirlpool, or vortex. The flow is fastest at the center and falls off as the radius increases. Indeed, if one rotates a container full of superfluid helium, even at a relatively low angular velocity, the stationary state of the liquid breaks down and tiny vortices form. Rotation, rather than being uniformly distributed through the liquid as in solid-body motion, penetrates the liquid along the vortex lines. The interaction among vortices and between vortices and the walls of a container creates some friction, and so the liquid is no longer completely superfluid.

The circulating flow associated with each of these miniature whirlpools repels its neighbors, so that the vortices form a regular hexagonal lattice. At typical experimental rotation speeds of 12 revolutions per minute, the distance between vortices is about .2 millimeter. (The vortex lattice in ^{4}He has been photographed directly by Richard E. Packard and his co-workers at the University of California at Berkeley.)

Vortices form easily in open volumes of superfluid, but confining the superfluid in a container filled with small particles—as might be done to demonstrate the fluid's vanishing viscosity—inhibits vortex formation. The liquid can flow between the particles without friction, but there is no space for a circulating flow to develop. This leads to a paradoxical situation: the finer the pores through which a superfluid must pass, the faster it can flow.

Superfluid vortices in ^{4}He are interesting enough; the internal structure of superfluid ^{3}He yields vortices that display even more complex behavior. Experimental study of such phenomena, however, is quite demanding. Not only must samples be cooled to a few millikelvins or less, they must also be rotated to produce the vortices. So far workers have only been able to solve this problem by rotating the entire experimental apparatus.

A large part of the data on vortices in ^{3}He has been obtained from the ROTA 1 cryostat in Helsinki, in use since 1981. It can produce rotation speeds as high as 30 revolutions per minute and temperatures as low as .6 millikelvin. An improved cryostat, ROTA 2, became operational in 1988. ROTA is a joint project between the Academy of Finland and the Soviet Academy of Sciences. Many individuals have participated in this experiment: M. Peter Berglund, Yuri M. Bun'kov, Devi Garibashvili, Pertti J. Hakonen, Olli T. Ikkala, Seppo T. Islander, Matti Krusius, Olli V. Lounasmaa, Yuri Mukharsky, Kaj K. Nummila, Jukka P. Pekola, Riita H. Salmelin, Juha T. Simola, Ladislav Skrbek, Jelil S. Tsakadze, among others. Theoretical contributions by Martti M. Salomaa, Grigory E. Volovik and their co-workers have also been decisive to the success of the ROTA project.

Four different experimental methods have been employed to explore the behavior of ^{3}He inside the rotating cryostat: nuclear magnetic resonance (NMR); the alternating-current (a.c.) gyroscope, which measures changes in the angular momentum of the superfluid; ion mobility, which acts as a sensitive probe of the fluid structure; and ultrasound, whose attenuation depends on the liquid's texture.

Most of what is known today about the effects of rotation in superfluid ^{3}He has been detected by NMR: the rotating ^{3}He is subjected to a steady magnetic field, which causes the axes of rotation of the nuclei to precess. A radio-frequency signal is employed to flip the nuclear spins. The particular frequencies that cause the spins to flip are a function of the interactions among the ^{3}He atoms.

Negative ions typically yield information about the texture of superfluid ^{3}He—the macroscopic alignment of spins and Cooper-pair orbital axes. Their motion through the fluid under the influence of an electric field depends strongly on the orientation of the field and the superfluid texture.

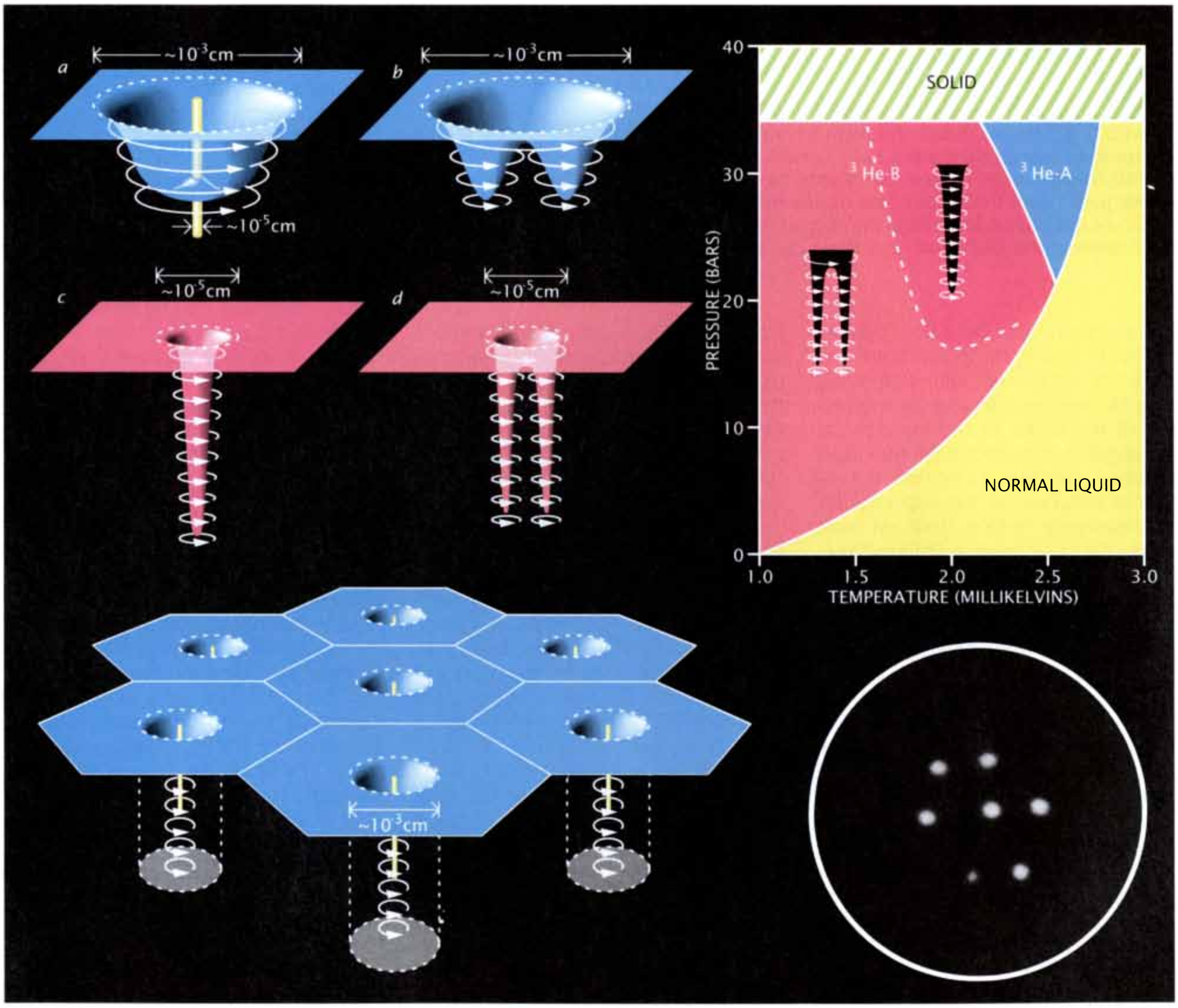
Similarly, the attenuation of ultrasound is a sensitive probe of the texture of ^{3}He superfluids. The advantage of ultrasound is that it can be employed in all magnetic fields. Systematic ultrasonic experiments have already been carried out in the ROTA 2 cryostat on vortices in ^{3}He-A in low magnetic fields and in yet another superfluid phase, $^3He\text{-}A_1$, which forms in strong magnetic fields.

The a.c. gyroscope, an experiment in which Packard participated, has been used to measure the flow properties of ^3He. The gyroscope consists of a horizontal torus filled with ^3He and plastic powder (to enhance superfluid flow) together with a drive mechanism for vibrating the torus and instruments to measure the superfluid's response.

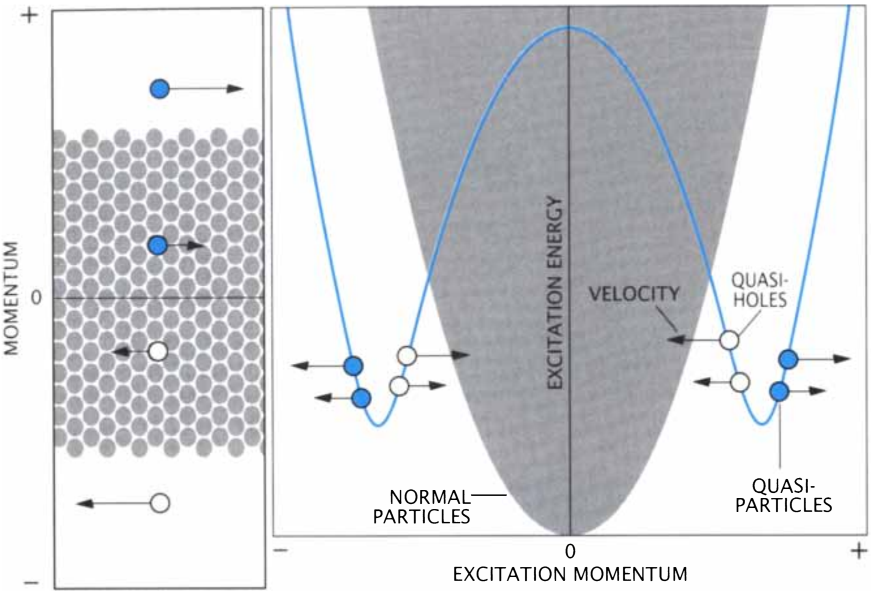
The first step in carrying out a typical gyroscope experiment is to cool the ^3He sample to well below the superfluid transition temperature while keeping the fluid at rest. Next the cryostat containing the torus (which holds the ^3He and plastic powder) rotates for about a minute at a rate between one and 20 revolutions per minute. During the five minutes following the end of the rotation, experimenters record the amplitude of vibrations around the vertical axis; these vibrations are caused by the precession of the spinning superfluid in the torus and are a measure of the angular momentum.

At low rotation speeds there is no angular momentum at all in the ring after the cryostat has been halted. When the cryostat rotates slowly, the superfluid simply slips frictionlessly through the pores of the plastic powder in the torus. Above a critical velocity of two to three revolutions per minute, however, vortices begin to form; the superfluid is dragged along and begins to rotate. An angular momentum persists in the torus after the cryostat is stopped.

One of the first experiments carried out with the gyroscope was a careful check for true superfluidity in liquid ^3He. The cryostat was rotated at its maximum speed to create a large angular momentum within the a.c. gyroscope; it was then brought to rest and the angular momentum measured. Af-



UNIQUE PROPERTIES of superfluid ^3He include the formation of at least four different kinds of vortices as the fluid is rotated. The quantum-mechanical properties of the liquid prevent it from rotating as a whole in the way that normal fluids do. A phase diagram (*upper right*) shows the conditions under which vortices form. $^3He\text{-}A$ can sustain vortices with either single cores (*a*) or double cores (*b*). The type of vortex that forms depends on the cooling history of the sample. The single-cored vortex is discontinuous: a minuscule thread of ordinary fluid runs through its center. The B phase also supports single-cored (*c*) and double-cored (*d*) vortices. The diameters of the $^3He\text{-}B$ vortices are much smaller than they are in the A phase, and both B-phase vortices are discontinuous. The fluid flows that make up individual vortices tend to repel each other, so that the vortices arrange themselves in a stable hexagonal lattice (*bottom*). Richard E. Packard of the University of California at Berkeley has photographed such a lattice in ^4He, which supports only one type of vortex (*lower right*).



UNPAIRED ATOMS in liquid ^{3}He form quasiparticles and quasiholes. Most atoms are bound in superfluid Cooper pairs (*gray*). Unpaired atoms have holes associated with them—empty states that would be occupied by the other atom in the Cooper pair. When the momentum of unpaired atoms is high, they stand out and appear as quasiparticles; when the momentum is low, the atoms merge into the low-momentum background, and their corresponding holes are visible instead.

ter the cryostat had been kept stationary for 48 hours, its temperature still below the superfluid transition point, workers measured the angular momentum of the liquid in the torus again. The angular momentum of the ^{3}He-B remained constant to within the 10 percent accuracy of the experiments. The resistance to flow deduced from this study is at least a trillion times smaller than that of normal liquid ^{3}He at the same temperature.

It is impossible to prove experimentally that ^{3}He-B has no resistance to flow whatsoever, but these results show beyond a reasonable doubt that ^{3}He-B is a true superfluid, not merely a normal liquid with very low viscosity. Peter L. Gammel, now at AT&T Bell Laboratories, and John D. Reppy of Cornell University, who used a somewhat different experimental arrangement, have seen persistent supercurrents in ^{3}He-A as well.

In other Helsinki experiments, we investigated additional details of vortex behavior. The critical velocity at which vortices begin to form and at which the B-phase superfluid is dragged along by the rotating gyroscope undergoes an abrupt change at certain temperatures and pressures. At a pressure of 23 bar and a temperature less than about 1.7 millikelvins, the critical velocity is 7.1 millimeters per second, whereas at a slightly higher temperature it is only 5.2. It appears that this sudden change in properties manifests the formation of different types of vortices in ^{3}He-B. The Helsinki group has discovered four different vortex types in superfluid ^{3}He, two in ^{3}He-A and two in ^{3}He-B, in contrast to the single kind that exists in ^{4}He.

In the A phase of ^{3}He, one of the vortex types is singular—it has a discontinuity in its core where the flow velocity changes direction abruptly—whereas the other type of vortex, which has a double core, is continuous. In the B phase both vortex types are singular—there is a discontinuity in the velocity field at the center. Complex theoretical analyses, first by Erkki V. Thuneberg of the University of Helsinki and then by Salomaa and Volovik, indicate that the vortex that forms at a lower critical velocity has a single, symmetric cylindrical core around which fluid flows, whereas the vortex that forms at a higher critical velocity has a double core.

Even when it is stationary, ^{3}He contains excitations. These excitations are associated with atoms that are not linked in Cooper pairs. Associated with each unpaired atom is a shadow particle—a "hole"—represented by the empty state of the atom it would have been paired with had the state been filled. These excitations combine the properties of a particle and a hole. At high momenta the particlelike properties dominate, and at low momenta the holelike properties dominate. An excitation thus is called either a quasiparticle or quasihole.

Much of the experimental data on the ballistics of quasiparticles in superfluid ^{3}He has been gained from the nuclear cooling cryostat built by Tony M. Guénault and one of us (Pickett) at the University of Lancaster. This apparatus, in operation since 1980, can cool liquid ^{3}He to around 100 microkelvins, where thermally generated excitations are scarce. Among those who have contributed to this work are John Carney, Kees Castelijns, Kenneth Coates, Shaun Fisher, Christopher Kennedy, Vepan Keith, Ian Miller, Simon Mussett, Gregory Spencer and Martin Ward. The nuclear cooling stage of this machine is unusual in that the copper cooling element is immersed directly in the liquid ^{3}He specimen, providing very good thermal contact.

Investigations of the samples cooled in this cryostat have been carried out by means of an extraordinarily simple yet versatile device (first developed by Mervyn Black, Henry Hall and Keith Thompson): a fine strand of superconducting wire bent into a semicircular loop and anchored at both ends [*see illustration on opposite page*]. If this wire is placed in a low-intensity magnetic field, then a current flowing through the wire will feel a force, and the wire will experience a sideways push.

An alternating current of the correct frequency can make the wire oscillate at its natural resonant frequency. Furthermore, as the wire moves in the field, it generates a voltage proportional to its velocity. The wire can be set in motion by sending a current through it and the response then observed by looking at the resulting voltage. This simple device has become the universal probe at very low temperatures in the Lancaster laboratory.

At low velocities the wire moves through the superfluid virtually without energy dissipation. The only friction comes from internal effects in the wire and its associated circuitry and from collisions with quasiparticles. The amount of damping is therefore proportional to the number of excitations in the liquid.

Because the number of quasiparticles changes with temperature, the wire can immediately be used as a thermometer. To be able to measure the temperature of the liquid directly at the lowest temperatures is obviously very important. It is almost impossible to get any other thermometric material into good thermal contact with the liquid ^3He at 100 microkelvins, because the density of the excitations—particles the thermometer can measure—in the superfluid is comparable to a very high vacuum at room temperature.

In addition to being almost the only device capable of measuring ^3He temperatures directly, the wire-loop thermometer is also quite sensitive. The damping falls some five orders of magnitude between the temperature of the superfluid transition and the lowest temperatures to which liquid ^3He can be cooled.

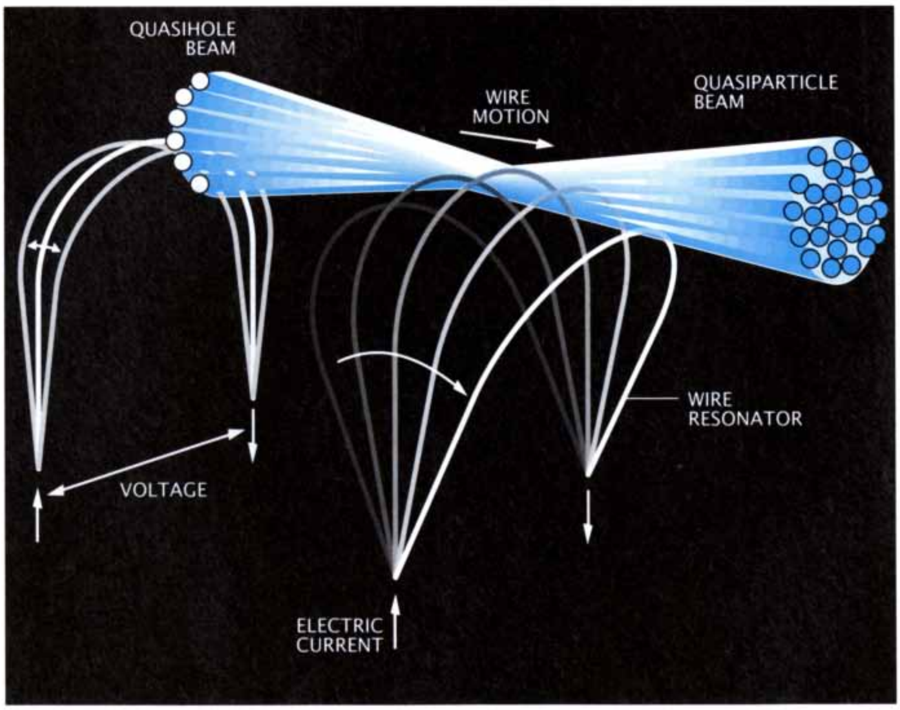
Even more important than the ability of the wire loop to determine the temperature of liquid ^3He is its potential for probing the structure of the liquid. Atoms in superfluid ^3He are bound in Cooper pairs; when the loop's maximum velocity exceeds about 10 millimeters per second, the wire can provide enough energy to break a pair into two atoms, or quasiparticles. At the lowest temperatures and low velocities, the wire's motion through the liquid is virtually frictionless. Once the wire reaches the critical velocity, however, the frictional force rapidly builds up by orders of magnitude, although the velocity increases by only a few percent. Because the change in damping is so catastrophic at the critical velocity, any anomalous flow of liquid around the wire (which would alter the wire's apparent speed) will markedly change the point at which damping builds up.

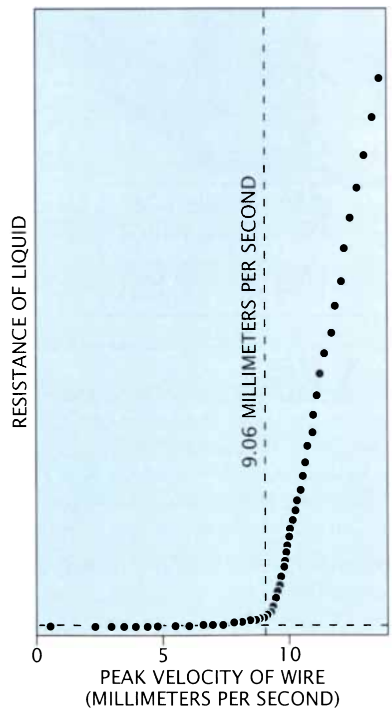
Pair breaking also provides a controllable source of artificially produced quasiparticles and quasiholes. The simplest picture of the pair-breaking process, developed by Canadian physicist Philip Stamp, suggests that the wire acts as a moving searchlight, emitting a beam of quasiparticles forward and a beam of quasiholes rearward. Not far below the superfluid transition temperature a large fraction of the particles is unpaired, and the mean free path between collisions is very short. Any quasiparticle "wind" will rapidly be scattered and dissipated by collisions with quasiparticles or quasiholes already present in the fluid. Yet if the temperature is reduced to one tenth of the superfluid transition temperature, only one in a million particles will be unpaired, and the likelihood of collisions will be so low that particles in the wind could travel for a kilometer or more without a collision.

Experiments at low temperatures have confirmed the basic accuracy of this picture. When a second wire is immersed in liquid ^3He, quasiparticles and quasiholes emitted by the first wire exert a force on the second wire, setting it in motion and generating a voltage. The second wire experiences a force directly proportional to the number of excitations striking it. The number of particles in the wind is in turn proportional to the energy dissipated by the first wire. Essentially all of the energy delivered to the first wire is converted into excitations, because there is no other mechanism for energy dissipation. We have also been able to confirm that the beam is narrow by looking at the angular distribution of the emitted quasiparticles.

Some puzzles still remain. Because the wire is moving back and forth, the pulsed beam of excitations emitted should consist of alternating bursts of quasiparticles and quasiholes. When a quasiparticle is scattered from a surface in a normal process, its momentum should simply be reversed, so that it applies a push to a reflector. A quasihole, in contrast, because its momentum and velocity point in opposite directions, applies a pull when reflected. Nevertheless, the detector wire experiences a push for bursts of either quasiparticles or quasiholes.

To see why this should be so requires a deeper understanding of the nature of particles and holes in ^3He. The concept of a hole arises from the nature of the lowest-energy level, or ground state, of a system of particles. In the lowest-energy state of a system of fermions, for example, particles fill all the states up to a certain energy lev-





SUPERCONDUCTING WIRE LOOP set in motion by current and magnetic field breaks up superfluid Cooper pairs to create beams of quasiparticles and quasiholes (*left*). A second loop can detect the resulting quasiparticle wind, whose motion yields data on the structure of the superfluid. Pair breaking increases rapidly as the wire exceeds a critical velocity (*right*).

el, determined by the number of particles, because each fermion must be in a different state. All higher-energy levels are empty. Such a ground state is what field theorists call a vacuum, because, as long as all the low-level states remain filled and no particle is boosted to an unfilled level, nothing can interact with it.

If a single fermion is removed from among the filled states and put in some higher-energy state, the situation changes markedly. The particle in the higher-energy level can now interact with various forces, and it leaves behind an empty quantum state—a hole. The particle and the hole behave in substantially different ways. Push a particle, and it moves away. Its momentum and energy increase or decrease together. Holes, however, do the opposite. Push a hole, and it approaches you. The momentum of a hole decreases as its energy increases, and vice versa. A hole behaves as if it had negative mass—indeed, it is a missing particle, so in a sense it does indeed have negative mass.

Unpaired particles in superfluid ^3He are particularly interesting. The Cooper pairs making up the superfluid part—the ground state—of the liquid consist of coupled particles with opposite momenta. As a result, unpaired atoms are coupled with a *hole* of opposite momentum or, if one prefers, an empty state where a particle of opposite momentum would properly be. This leads to very unusual behavior.

For a normal particle, the relation between energy and momentum is simple. Both rise and fall in step. The situation for ^3He quasiparticles is not so straightforward. An unpaired atom whose momentum is high stands out because other high-momentum states are empty, whereas the associated hole (a state without an atom in it) is indistinguishable from other empty high-momentum states. The particle-hole combination looks exactly like a real particle, and its energy increases with momentum. An unpaired atom whose momentum is low, in contrast, is indistinguishable from the myriad of paired low-momentum particles; it is the low-momentum hole (moving in a direction opposite to that of the particle) that stands out. And the hole's energy increases as its momentum falls. Between these two extremes is a point where the energy of the particle-hole combination falls to a minimum and its velocity falls to zero.

The direction of a quasiparticle's velocity at low momenta (when it appears as a hole) is opposite to its direction at high momenta (when it appears as a particle). As a result, a quasiparticle that enters a region where there is a force opposing its motion will gradually lose energy until its velocity reaches zero. Its hole properties then begin to dominate, its velocity reverses and it retraces its path. In effect, the force smoothly converts the quasiparticle into a quasihole, and vice versa. This process, which has no analogy in the scattering of normal particles, is called Andreev reflection after Aleksander F. Andreev of the Institute for Physical Problems in Moscow, who first suggested the mechanism in the context of superconductors.

Andreev reflection may account for the fact that the second wire in the quasiparticle-beam experiment senses a push from both quasiparticles and quasiholes. When quasiparticles are converted to quasiholes by Andreev reflection at the second wire, the wire experiences a push; the wire is also pushed when quasiholes are converted to quasiparticles. This is unlike the normal process, where the two types of excitation produce opposite effects.

The two-wire device does more than simply demonstrate the bizarre behavior of quasiparticles and quasiholes. It provides all the components needed to study the dynamics of quasiparticles in superfluid ^3He. It has a source and a detector, and the whole system operates at a temperature of about 100 microkelvins.

Laboratory studies of the behavior of superfluid ^3He may eventually yield insight about forms of matter found nowhere on the earth. It is conjectured, for example, that the neutron matter (neutronium) in rapidly rotating pulsars is superfluid, even though the temperature in neutron stars is about 100 million kelvins. Neutron matter clearly cannot be studied in the laboratory, but it may be possible to mimic its behavior by means of rotating superfluid ^3He or ^4He. Neutrons, like ^3He atoms, are fermions, and it is believed that neutronium becomes superfluid by the same Cooper-pair mechanism operating in ^3He. Only detailed theoretical calculations can tell whether the correspondence between superfluid ^3He and neutronium is sufficiently close for such models to yield useful results. If so, experiments will be performed on ^3He with neutron stars in mind.

What are the chances of finding other superfluids on the earth? One strong candidate is a dilute solution of ^3He in superfluid ^4He. Depending on the pressure applied, solutions can be made containing up to 10 percent ^3He. At some sufficiently low temperature, the ^3He atoms in the solution should form Cooper pairs and become superfluid. Despite investigations by several laboratories, no such transition has so far been observed. The density of ^3He atoms in a solution of this kind is very low, and the interactions between them are quite weak. Estimates of the transition temperature lie in the nanokelvin regime, far below the 80 to 100 microkelvins to which dilute solutions of ^3He in ^4He have so far been cooled.

Such a superfluid could open up entirely new realms of atomic behavior. Not only would the ^3He atoms become superfluid, but they also would do so in a superfluid solvent. The new system would comprise two interpenetrating yet independent superfluids. Such a two-component superfluid is bound to have even more bizarre behavior than the single-component ones now known.

Furthermore, theory suggests that two different kinds of Cooper pairs could form in a dilute solution of ^3He. The dominant type in any given solution would depend on the concentration of ^3He. At high concentrations, pairs would form with the nuclear spins of the two atoms parallel, as in pure ^3He. At lower concentrations, however, pairs with opposing spins should form instead. At some intermediate concentration the two kinds may coexist side by side, yielding a three-component superfluid.

The experimental verification of such a possibility may lie far in the future, because such a transition may take place only at temperatures well below those to which liquid helium can be cooled at present. Nevertheless, there is little doubt that those temperatures will eventually be reached.

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