Superfluid Helium 3

At a temperature a few thousandths of a degree above absolute zero this isotope of helium becomes able to flow through tiny pores without friction and exhibits bizarre magnetic effects

by N. David Mermin and David M. Lee

One of the less publicized frontiers of physical science lies in the realm of ultralow temperatures. This frontier opened up in 1911, when the first liquefaction of gaseous helium made it possible to achieve temperatures as low as a few degrees Kelvin (degrees Celsius above absolute zero). Today cryogenic techniques have progressed to the point where the properties of matter can be studied down to temperatures within a few thousandths of a degree above absolute zero.

There is a powerful incentive for performing such experiments. The behavior of matter is governed by the fundamental system of physical laws known as the quantum theory. Although all matter is subject to the laws of the quantum theory, ordinarily those laws are most strikingly manifested only on the microscopic scale of atoms and their constituent particles. Quantum effects are also displayed in the behavior of bulk matter, but the most spectacular and most interesting of such effects are obscured or even completely obliterated by the random thermal agitation of the atoms. Every advance in cryogenic techniques that lowers the range of accessible temperatures by another factor of 10 pulls back the curtains around still another level of bulk quantum behavior, often with quite unpredictable scientific and technological benefits.

The phenomenon known as superfluidity is probably the most spectacular example of quantum behavior in bulk matter that research at low temperatures has yet uncovered. Superfluidity is displayed within a few degrees of absolute zero by helium 4, the liquid form of the most abundant isotope of helium, the isotope with mass number 4. Under the name of superconductivity, superfluidity is also displayed by the conduction electrons in a great many metals and alloys, at temperatures that depend on the particular material but that are never more than about 25 degrees above absolute zero.

Superfluids contradict all intuition about how matter ought to behave. A superfluid can move in apparent defiance of the ordinary laws of friction, flowing effortlessly past obstructions sufficient to retard or entirely block the flow of a normal liquid. Superfluids can establish persistent circulatory currents that show little if any tendency to die away. When a vessel containing superfluid helium 4 is slowly rotated, the liquid may refuse to participate fully in the rotation. In a somewhat similar display of abnormal behavior the electron fluid in a superconducting metal may refuse to allow an external magnetic field to penetrate the metal. When the field is applied, the electrons, which carry an electric charge, produce whatever electric currents are required to generate an opposing field of the same strength as the applied one. The external field is canceled by this internal one and is therefore unable to penetrate the superconducting medium.

Until a few years ago superfluidity had been observed only in helium 4 and in superconductors. In 1971, however, a third form of superfluidity was discovered in liquid helium 3, the lighter and much rarer of the two nonradioactive helium isotopes. Since two isotopes of the same element ordinarily have quite similar properties, this might not seem a significant discovery. The two helium isotopes, however, are exceptions to the rule: their solid and liquid forms differ strikingly in almost all properties. Indeed, from the mid-1930's to the mid-1950's there was good reason to believe helium 3 could not become a superfluid, and it is now known that the mechanism for superfluidity in helium 3 is very different from that in helium 4.

In fact, the recent discovery of superfluidity in helium 3 has furnished us with a spectacularly different superfluid. Although the two helium superfluids share many characteristic superfluid flow properties, to bring about superfluidity in helium 3 requires a temperature almost 1,000 times lower than that needed to do so in helium 4. Where liquid helium 4 has one normal phase and one superfluid phase, helium 3 has a normal phase and three distinct superfluid phases. The helium-3 superfluids are magnetic. Furthermore, the superfluid phases of helium 3 are inherently anisotropic: measurements of their properties made in one direction can give quite different results from the same measurements made in other directions. These curious phenomena, like those seen in superfluid helium 4 and in superconductors, are all related to direct macroscopic manifestations of the quantum theory. Indeed, the quantum theory must be invoked even to explain the sizable differences between the two normal helium liquids, and for that matter to explain why they are liquid at all.

The Two Helium Isotopes

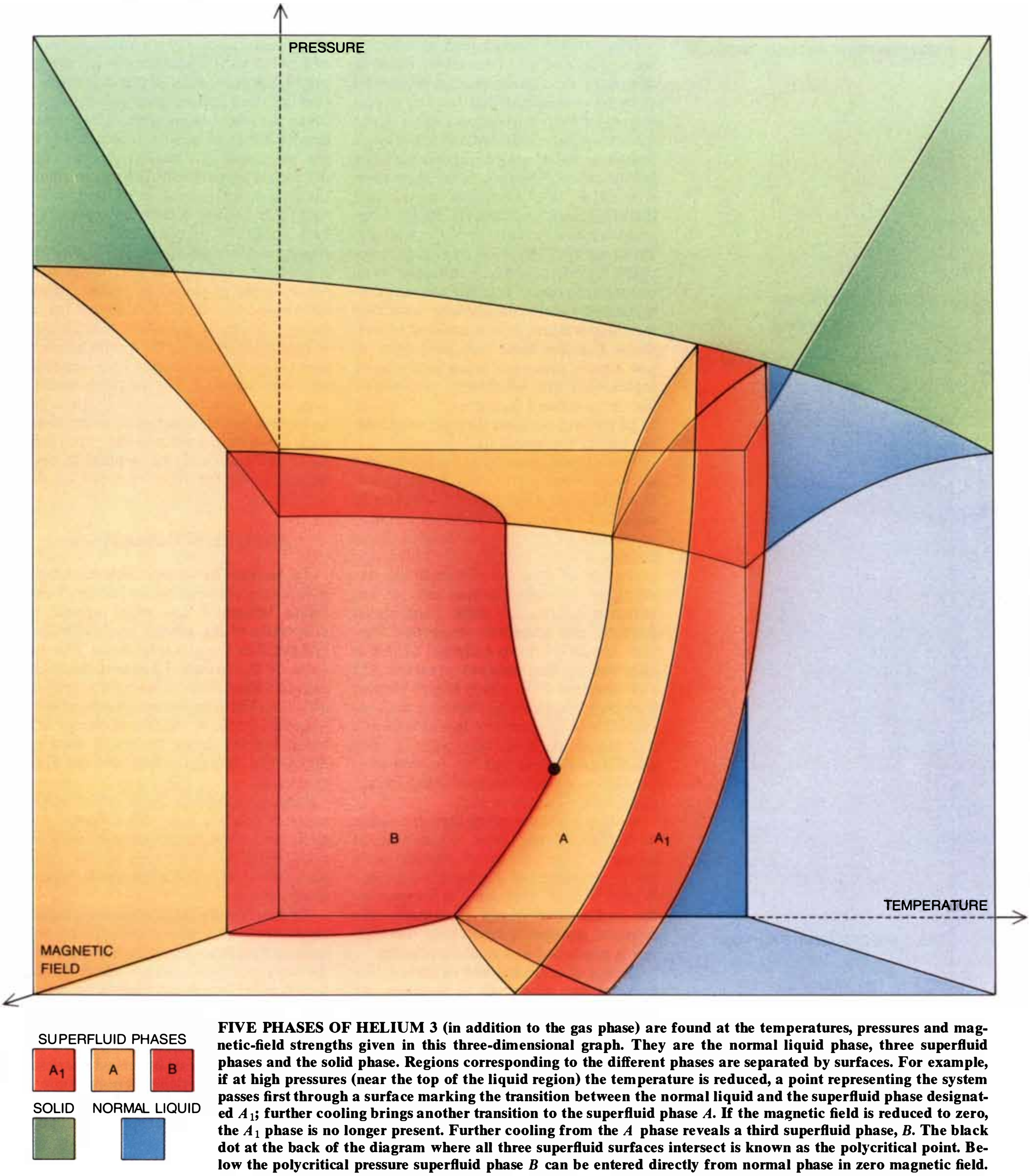
The helium isotopes are unique among all known liquids in refusing to freeze at ordinary pressure no matter how low the temperature; in principle they could be cooled all the way to absolute zero and still remain liquid. Solid helium can be formed only by cooling the liquid under pressure.

Cooling a substance reduces the average kinetic energy of its atoms or molecules; if the temperature is made low enough, the molecules lack the kinetic energy needed to overcome the intermolecular forces tending to bind them rigidly together. The molecules then lose their mobility and are confined to fixed positions: the substance becomes solid.

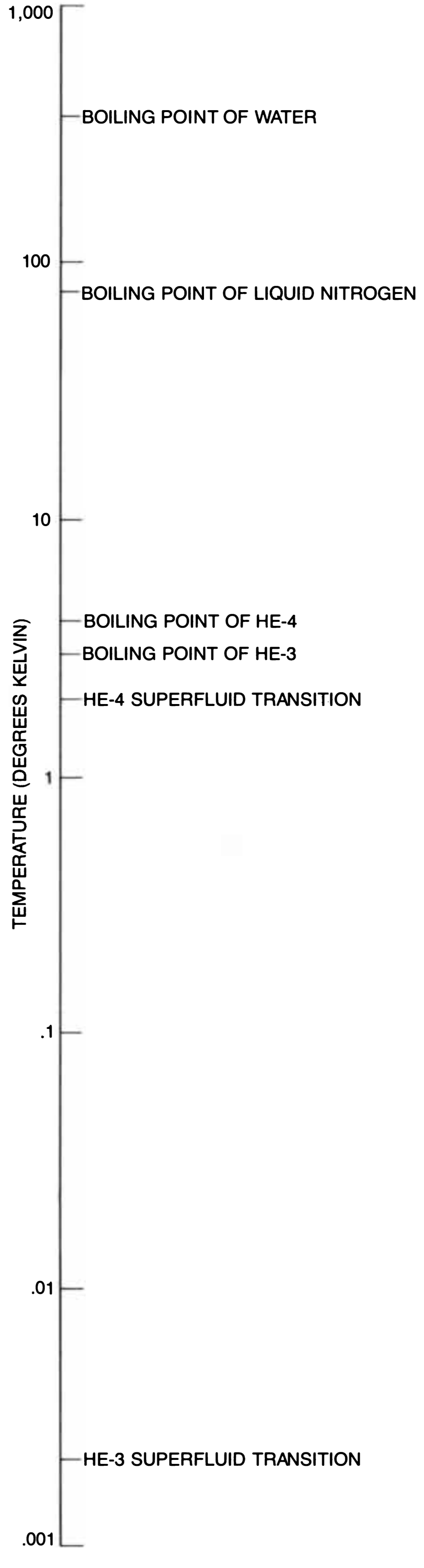
The failure of helium to freeze is due in part to the feebleness of the forces between its atoms. Helium is one of the inert or noble gases, the group of elements that also includes neon, argon, krypton and xenon. The interatomic forces in all these elements are exceptionally weak. Yet all but helium do freeze without the application of pressure if the temperature is low enough.

The failure of helium to solidify is perhaps the simplest way in which this extraordinary substance reveals the laws of the quantum theory at work. In liquid helium, no matter how low the temperature, the atoms retain enough kinetic energy to overcome the attractive interatomic forces. This blatantly contradicts the classical (that is, pre-quantum-theoretical) view that at absolute zero the average kinetic energy is necessarily zero, so that the atoms sit motionless at fixed positions.

According to the quantum theory, this prediction is not precisely correct because it conflicts with the uncertainty principle, which states that the position and the momentum of a particle cannot be simultaneously specified with unlimited accuracy. In particular, if the position of an atom is rather precisely known, as it is in a solid, then the momentum or the kinetic energy of the atom must be uncertain by some small



FIVE PHASES OF HELIUM 3 (in addition to the gas phase) are found at the temperatures, pressures and magnetic-field strengths given in this three-dimensional graph. They are the normal liquid phase, three superfluid phases and the solid phase. Regions corresponding to the different phases are separated by surfaces. For example, if at high pressures (near the top of the liquid region) the temperature is reduced, a point representing the system passes first through a surface marking the transition between the normal liquid and the superfluid phase designated A_1; further cooling brings another transition to the superfluid phase *A*. If the magnetic field is reduced to zero, the A_1 phase is no longer present. Further cooling from the *A* phase reveals a third superfluid phase, *B*. The black dot at the back of the diagram where all three superfluid surfaces intersect is known as the polycritical point. Below the polycritical pressure superfluid phase *B* can be entered directly from normal phase in zero magnetic field.



TRANSITION TEMPERATURES for liquid-vapor phase changes in helium are the lowest of those for all the elements; at the boiling point of helium all other substances are frozen. Superfluid transition temperature of helium 3 is roughly 1,000 times lower than that of helium 4. The temperatures are on the Kelvin scale, in which absolute zero (−273.15 degrees Celsius) is taken to be zero degrees.

but finite amount. Conversely, a particle cannot have exactly zero kinetic energy and at the same time occupy a definite position. In the well-ordered crystalline array of the solid state the position of an atom is specified with great precision, and so the kinetic energy cannot be precisely zero. Even at absolute zero the atoms retain a certain "zero-point kinetic energy" and are therefore not altogether stationary.

Other things being equal, an object's zero-point energy increases as its mass decreases. Zero-point motion is so small as to be inconsequential for any object of greater than microscopic mass. Even the zero-point motion of a single atom is generally not of major importance. The helium atom, however, is the least massive of all the noble-gas atoms and therefore has a relatively large zero-point motion. Except at high pressures the combined effect of this large zero-point motion and the extremely weak interatomic forces is to prevent the formation of a stable solid phase, whatever the temperature. It is a curious coincidence that the same two properties of low atomic mass and weak interatomic forces that are ultimately responsible for the profound importance of helium to physicists are also directly responsible for its usefulness in balloons.

Quantum-mechanical effects not only are responsible for the instability of solid helium but also must be invoked to explain why even the simplest physical properties of the isotopes helium 3 and helium 4 differ significantly. With the exception of their atomic mass the isotopes of a single element are all but indistinguishable in their commonest physical and chemical properties. Perhaps the best-known example of this is afforded by the isotopes uranium 235 and uranium 238, which are so similar that merely separating them requires heroic efforts. Mixtures of liquid helium 3 and helium 4, in striking contrast, can spontaneously separate at certain temperatures, the two isotopes being immiscible, like oil and vinegar.

In nature almost all helium is helium 4; helium 3 has been obtainable in amounts large enough to provide more than a few drops of the liquid only since World War II. Helium 3 is formed by the radioactive decay of tritium, the heaviest isotope of hydrogen; the tritium is produced in a nuclear reactor.

Atoms of helium 3 and helium 4, like those of any other pair of isotopes, are almost identical in structure apart from the tiny central nucleus. Except for the nucleus each atom consists of a cloud of negative electric charge generated by two electrons, and for two isotopes of the same element these electron clouds are virtually indistinguishable in size and shape. In general two isotopes of the same element are so similar because most of the familiar physical and chemical properties of an element are determined entirely by its electronic structure. The chemical inertness of both helium 3 and helium 4 is one example of such similarity, but in almost all other respects the liquid forms of the two isotopes are surprisingly different.

The disparate behavior of the two isotopes is surprising because the only significant difference between them lies in the nuclei of the atoms. Helium 4 has two protons and two neutrons in its nucleus; helium 3 has two protons but only one neutron. If quantum effects are ignored, the only result of this difference is that helium 3 is the lighter substance, its mass per atom being about 25 percent less than that of helium 4. According to the principles of classical physics, this difference in mass should have no effect on the thermal properties of the two liquids. Yet helium 3 boils at a temperature about 25 percent lower than the boiling point of helium 4, and it requires a pressure roughly 25 percent greater for its solid phase to be stable. These discrepancies can be accounted for in large measure by the effect of the atomic-mass difference on the quantum zero-point energy. Since helium 3 is less massive than helium 4, its zero-point motion is greater. Therefore helium-3 atoms require less thermal energy in order to escape from the liquid into the vapor and more pressure must be applied to confine them to the rigid network of the solid state.

Properties of Helium Nuclei

To account for most of the remaining differences between liquid helium 3 and liquid helium 4 one must appeal to properties of the atomic nucleus rather less familiar than its total mass. The nucleus of the helium-3 atom spins on its axis at a fixed and permanently unalterable rate, like a gyroscope provided with a specified dose of rotational energy and freed forever from frictional slowing down. The nucleus of helium 4 does not spin at all.

Closely related to the presence or absence of nuclear spin, the helium-3 nucleus is a permanent magnet, with its poles lying along the axis of spin rotation. The nucleus of a helium-4 atom is nonmagnetic.

To describe the most important difference between the nuclei of helium 3 and helium 4 we must examine more closely the way particles are described by the quantum theory. According to the quantum theory, properties are allotted to particles and atoms only in discrete units, or quanta. Electric charge is a familiar example: in all observed particles and systems of particles its magnitude is invariably some integral multiple of the electric charge of an electron or a proton. This fact can be conveniently expressed by assigning every particle an electric-charge quantum number, which simply gives the magnitude of that particle's charge and can assume only the discrete values observed.

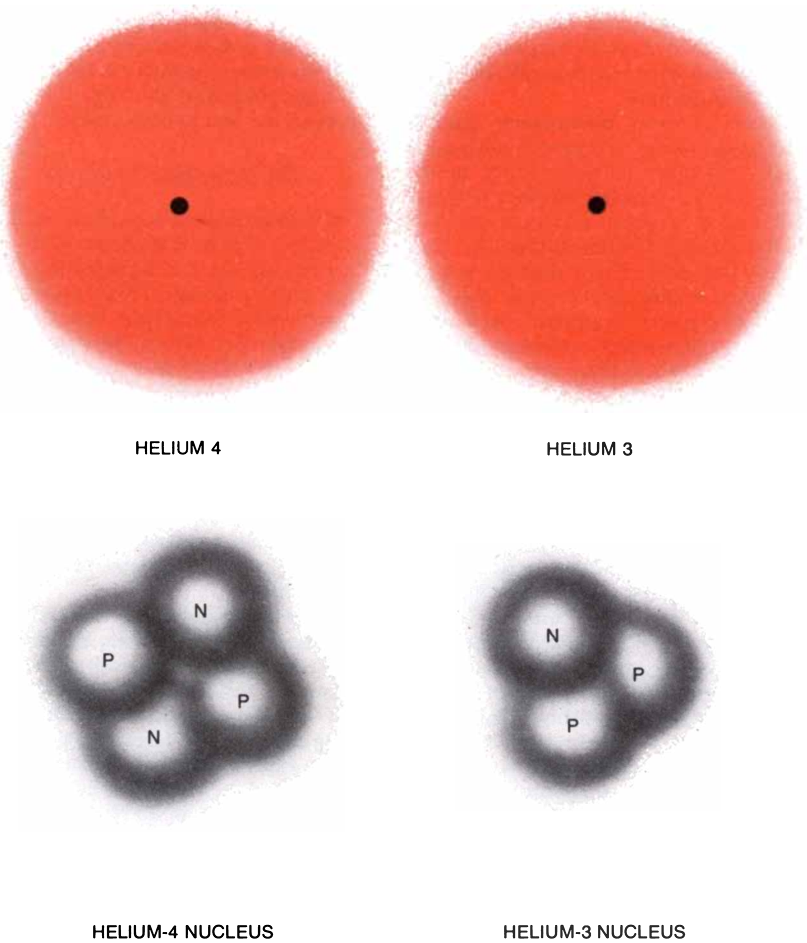
A less familiar and rather more startling example is the fixed and permanently unalterable rate at which spinning particles do their spinning. These rates are also confined to a set of discrete possible values, and the value that characterizes the spin of a given type of particle is as permanent a property of that particle as its electric charge.

The charge and spin of a particle are examples of quantum numbers with a single definite value that is characteristic of that species of particle. There are other quantum numbers, however, that can have a range of discrete values for a given particle. These quantum numbers specify the motion of the particle as a whole. Their values give information about the position or momentum of the particle.

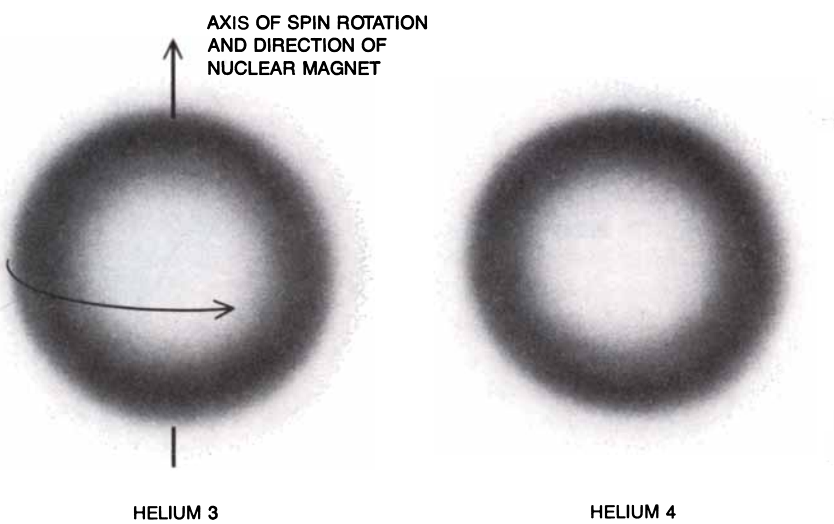
All the information it is possible to collect about what a particle is doing at any moment can be expressed by listing the values of all the particle's quantum numbers. Such a list of quantum numbers is said to define the state of the particle. A specification of a particle's state contains everything it is possible to say about the particle, including (within the limits set by the uncertainty principle) information about its position, its momentum and its kinetic energy.

In describing liquid helium 3 or liquid helium 4 or in describing the conduction electrons in a superconducting metal one is studying the behavior of large groups of identical particles. There is a class of elementary particles known as fermions, of which electrons, protons and neutrons are the most familiar and important examples, whose behavior in the aggregate is limited by the rule that no two fermions of the same type can be in precisely the same state. Given two electrons, for example, at least one of their quantum numbers must differ. No two fermions can behave exactly the same way. The application of this law to the orbits of electrons in atoms is fundamental to the theoretical explanation of the periodic table of the elements, but it also comes into play in many less familiar contexts and is of fundamental importance in understanding the difference in the properties of liquid helium 3 and liquid helium 4.

Not all elementary particles are fermions. There is a second class of particles called bosons, of which photons and pi mesons are examples. Although two fermions are prohibited from being in the same state, for bosons there is no equivalent principle of segregation. Bosons can be brought together in a single state in unlimited numbers. Indeed, under certain conditions a significant fraction of all the bosons in a large system of particles can occupy precisely the same quantum state. This bunching of bosons into the same quantum state is known as Bose-Einstein condensation. A collec-



ELECTRONIC STRUCTURES OF HELIUM ISOTOPES are almost precisely the same. The atoms of both helium 4 and helium 3 have two electrons, which form a spherical cloud of negative electric charge surrounding the nucleus (*top*). The two atoms differ significantly only in their nuclei, which are about 100,000 times smaller in diameter than the surrounding electron clouds. The helium-4 nucleus consists of two protons and two neutrons; the helium-3 nucleus has two protons but only one neutron (*greatly enlarged at bottom*). The physical and chemical properties of all other materials are determined almost entirely by the electronic structure of their atoms, but in helium the differences in nuclear structure give rise to many pronounced differences in behavior of both the liquid and the solid forms of the two isotopes.



NUCLEAR PROPERTIES of helium 3 and helium 4 differ. The helium-3 nucleus spins like a gyroscope and behaves magnetically as if it were a permanent bar magnet oriented along the axis of spin rotation. The vertical arrow indicates the direction of a magnetic pole; the equatorial arrow indicates the spin. The helium-4 nucleus possesses neither spin nor magnetism.

tion of bosons may or may not be Bose-Einstein condensed. For a system of fermions, however, such condensation is strictly prohibited.

Every known elementary particle (and according to current theoretical views, all those particles yet to be discovered or invented) is either a boson or a fermion. Nuclei or atoms (such as those of either helium isotope) are composite particles. Every nucleus is composed of elementary protons and neutrons, and every atom has in addition a cloud of elementary electrons surrounding its nucleus. Atoms are hence composed of three types of elementary particles, all of which are fermions.

The aggregate behavior of identical composite particles made out of two or more fermions is subject to the same restrictions as the behavior of elementary particles. Whether such composite particles are bosons or fermions is determined by a very simple rule: Particles composed of an odd number of fermions (of which a single fermion is the simplest example) behave like fermions, whereas particles composed of an even number of fermions behave like bosons. Thus helium 4, consisting of two electrons bound to a nucleus of two protons and two neutrons, is a boson because it is composed of six fermions, whereas helium 3, with one less neutron in its nucleus, is composed of only five fermions and is therefore itself a fermion. It is this arcane distinction that leads to the most profound of all the differences between the two helium liquids.

The Superfluid Transition

Manifestations of superfluid behavior in helium 4 were first observed in 1911 shortly after the first liquefaction of helium, and by the late 1930's most of the characteristic superfluid behavior had been observed. When the temperature of liquid helium 4 falls below 2.17 degrees Kelvin there is a sudden and discontinuous change in its properties. Below this transition temperature liquid helium 4 abruptly becomes a perfect conductor of heat, and it acquires the ability to leak with frictionless ease through minute cracks and pores that are completely impenetrable at higher temperatures.

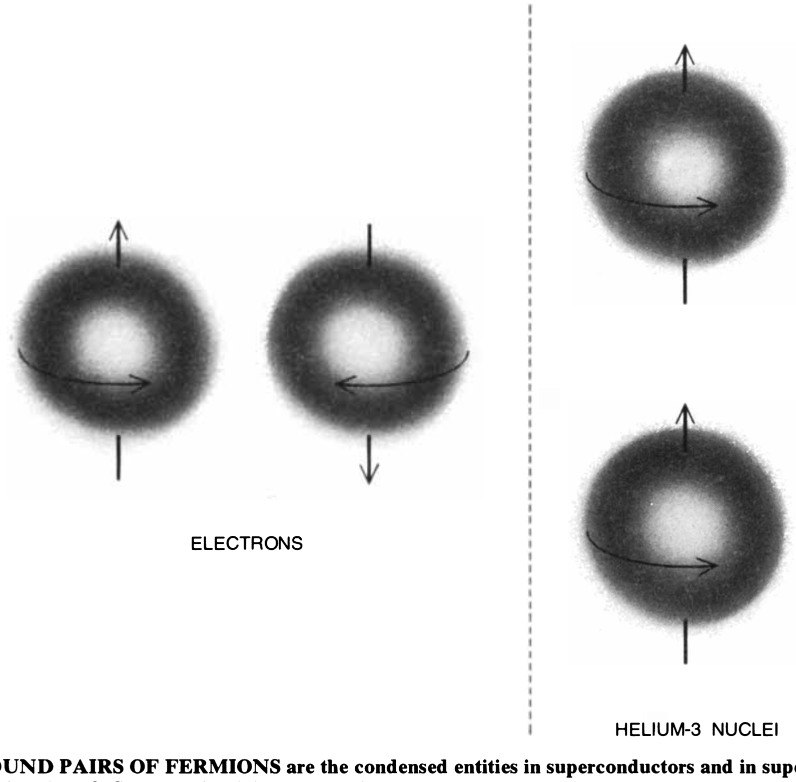
It was suggested in the 1930's that the superfluid transition in liquid helium 4 might be related to Bose-Einstein condensation, and it was recognized that if that were the case, then liquid helium 3, being composed of fermions, should not have a superfluid phase. The acquisition of helium 3 in quantities large enough for studies of the liquid phase was therefore eagerly awaited. In the 1950's it was established that no transition to a superfluid took place in helium 3 anywhere near 2.2 degrees. Subsequent experiments revealed that helium 3 could be cooled to temperatures below a hundredth of a degree without showing the slightest signs of superfluidity. These findings were taken as evidence that Bose-Einstein condensation does play a vital role in the superfluidity of helium 4, and today opinion is virtually unanimous that superfluid helium 4 is a liquid that has undergone Bose-Einstein condensation. The subsequent discovery of superfluidity in helium 3 at a few thousandths of a degree above absolute zero has not shaken that conviction. The mechanism underlying this superfluidity is quite different.

To indicate why Bose-Einstein condensation might lead to the characteristic superfluid properties of helium 4, it may help to consider an analogy with a more familiar system in which quantum-mechanical effects influence the bulk properties of matter. When André-Marie Ampère proposed in the 19th century that the magnetism of permanent magnets might arise from the flow of persistent microscopic electric currents, it was objected that such currents would rapidly dissipate their energy into heat and therefore cease. Ampère boldly ignored this difficulty, and his view was eventually vindicated by the quantum theory. Since physical properties on the atomic scale can vary only by discrete amounts, the gradual and continuous erosion of an atomic current by friction is impossible. In the realm of individual atoms, where properties are specified by discrete quantum numbers, things do not wear out; they either remain perfectly unaltered or are abruptly transformed into different things. If, as is often the case, there are reasons why none of a set of discrete alternative states is allowed, then no change whatever can occur.

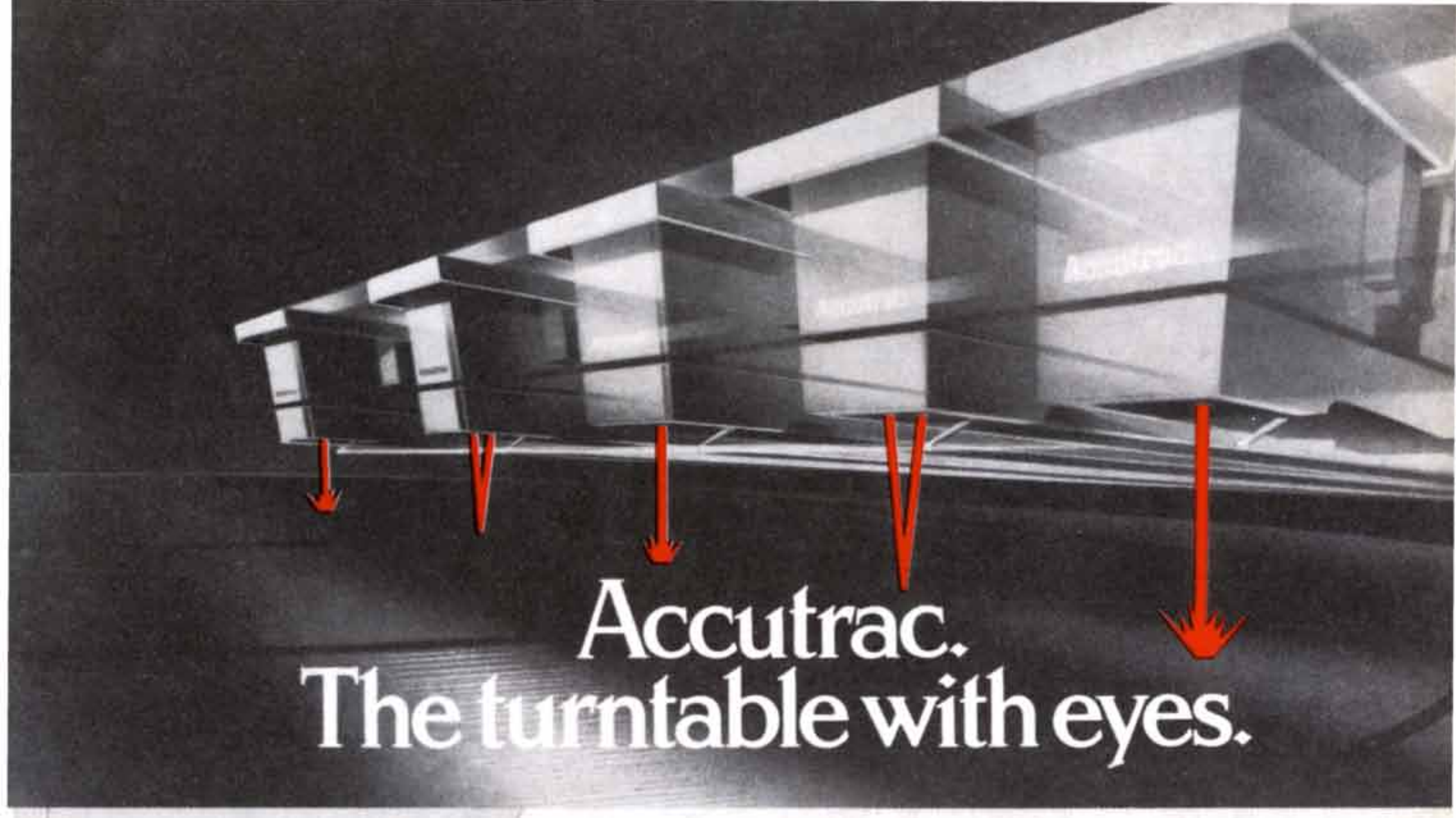
This characteristic discontinuity and rigidity of atomic processes is indiscernible in ordinary bulk matter because the number of atoms it contains is so vast that although every atom obeys quantum laws, the combined effect of their discontinuous behavior is indistinguishable from perfect continuity. In a permanent magnet, however, the microscopic atomic currents described by Ampère are all flowing in such a way as to reinforce one another.

Similarly, in a system that is Bose-Einstein condensed, an appreciable fraction of all the atoms behave as if they were in precisely the same quantum-mechanical state, and as a result their motions are highly correlated. They are, as it were, marching in lockstep and can therefore reinforce one another's characteristic quantum properties, which can then be observed in the macroscopic behavior of the system.

The frictionless flow of superfluid he-



BOUND PAIRS OF FERMIONS are the condensed entities in superconductors and in superfluid helium 3. Superconductivity appears in a metal when the temperature falls low enough for the electrons to form bound pairs under the influence of a weak attractive force. In a like manner superfluidity appears in liquid helium 3 when pairs of atoms become bound together. In a bound electron pair in a superconductor the elementary magnets oppose each other, and the pair has no net intrinsic magnetism. The electrons also spin in opposite directions. The bound pairs of helium-3 atoms are quite different. The magnets reinforce each other, and as a result the pair possesses a net magnetism. Helium-3 nuclei also have same direction of spin.



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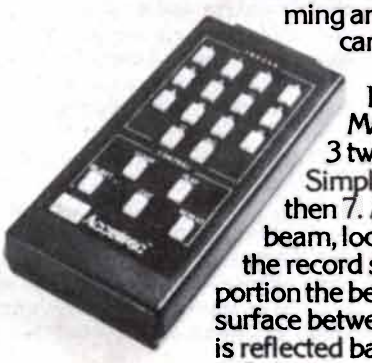

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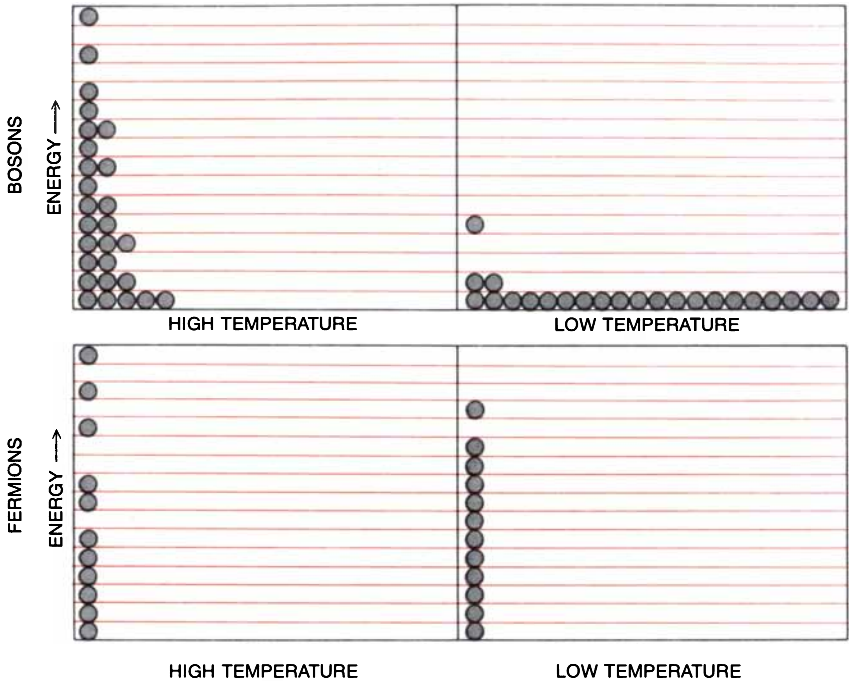

COLLECTION OF BOSONS is subject to quantum laws different from those that apply to a collection of fermions. Any number of bosons can have exactly the same set of quantum numbers, and at very low temperatures it is possible for an appreciable fraction of them to be in precisely the same state. Fermions obey a different rule: Only one fermion can have a given set of quantum numbers, so that it is never possible to have more than one fermion in a given state. In one simple model these rules lead to the following distinct kinds of behavior. At high temperatures the bosons are distributed over many states, which may or may not be occupied by more than a single boson. At low temperatures only the states of lowest energy are occupied appreciably, and number of bosons in state of lowest energy may actually be comparable to total number of bosons in system. Since only one fermion can occupy a given state, all that can happen as temperature drops is that occupied states settle down to group lying lowest in energy. Energy cannot be further reduced by assigning more than one fermion to lowest states.

	HELIUM 4	HELIUM 3	SUPERCONDUCTORS
TRANSITION TEMPERATURE (DEGREES KELVIN)	1.75 TO 2.2	.001 TO .0027	0 TO 23
ELEMENTARY PARTICLES OF FLUID	ATOMS	ATOMS	ELECTRONS
MAGNETIC	NO	YES	YES
STATISTICS	BOSON	FERMION	FERMION
ELECTRIC CHARGE	NO	NO	YES
CONDENSED ENTITIES	ATOMS	PAIRS OF ATOMS	PAIRS OF ELECTRONS
SPATIALLY SYMMETRIC	YES	NO	YES
MAGNETIC	NO	YES	NO
EXPEL MAGNETIC FIELD	NO	NO	YES
NUMBER OF SUPERFLUID PHASES	ONE	THREE	ONE

PROPERTIES OF SUPERFLUIDS are determined by the nature of the particles making up the fluid and by the manner in which those particles condense to form the superfluid phase. Superfluid helium 4 is formed through the Bose-Einstein condensation of single helium-4 atoms, which are neutral, nonmagnetic, spinless bosons. In a superconductor the condensed entities are pairs of electrons. The electrons are electrically charged, but the magnetism associated with the electron spin cancels within each pair. Superfluid helium 3 has some features of superfluid helium 4 and some features of a superconductor, but it also has features that are not shared by either of the other two superfluids. Because the pairs are not spatially symmetrical the properties of superfluid helium 3 can show a pronounced dependence on direction; because the pairs are magnetic an entire new category of macroscopically observable quantum behavior has been made available; because the fluid allows the introduction of a magnetic field new magnetic phenomena can be conveniently observed, and because there are three superfluid phases macroscopic quantum behavior is made available for study in a variety of forms.

lium through tiny cracks can be viewed as being analogous to the Ampèrean current in a permanent magnet. In both cases microscopic quantum behavior is amplified to the macroscopic scale. In the case of the magnet the amplification is brought about by the orderly arrangement of the individual atomic currents; in the case of superfluid helium 4 it is produced by the Bose-Einstein condensation of the atoms.

Those who enjoy pondering the mysteries of the quantum theory might pause at this point to contemplate the difference in the behavior of the two helium liquids at temperatures from about .01 degree to two degrees above absolute zero. Liquid helium 3 behaves quite properly; indeed, it gets somewhat sluggish as the temperature drops, becoming as viscous as light machine oil. Liquid helium 4, however, slips through infinitesimal cracks so tiny as to be impenetrable even by a gas, and it otherwise disports itself in unexpected ways. Yet the atoms out of which the two liquids are formed are identical in almost all respects. The only difference is buried deep in the atomic interior. There, well shielded by the almost impenetrable cloud of electrons, in a nucleus that occupies only a billionth of a millionth of the volume of the entire atom, helium 3 lacks a neutron.

Superconductivity

In spite of the early failures to discover a superfluid transition in helium 3, the substance was of considerable interest as a system of fermions that remains in the liquid state even at absolute zero. Although helium 3 is the only conventional liquid to behave this way, analogous systems of fermions are formed by the conduction electrons in metals, by the protons and neutrons in large atomic nuclei and by the neutrons that compose the matter in a neutron star. As a result liquid helium 3 has been of considerable interest to solid-state physicists and of occasional interest to nuclear physicists and astrophysicists. The interplay through the 1950's and 1960's between the study of liquid helium 3 and the study of electrons in metals has been particularly fruitful, in part because helium is in many ways the simpler system. Conduction electrons have a negative electric charge and exist only within a matrix of positively charged metal ions. Helium-3 atoms, on the other hand, are electrically neutral and can be studied in the pure state, contaminated only by a few stray atoms of helium 4.

The possibility that helium 3 might be a superfluid after all arose from this analogy between helium-3 atoms and conduction electrons. We have noted that in many metals the conduction electrons enter a state of electronic superfluidity, or superconductivity, when the metal is cooled to very low tempera-

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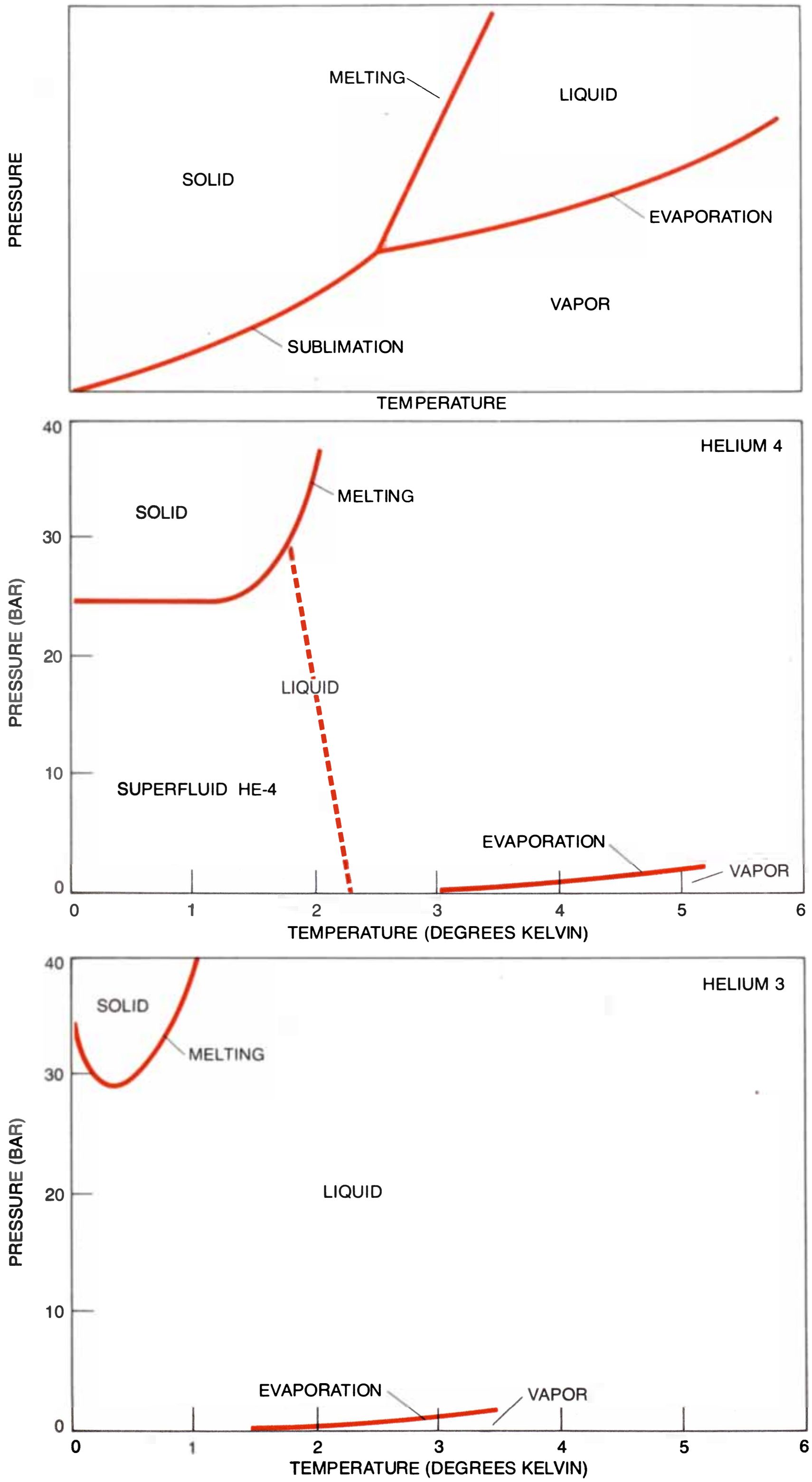


PHASE DIAGRAMS portray the state of a substance at various temperatures and pressures. In most substances (*top*) the liquid phase cannot exist at low temperature, no matter what the pressure is. A familiar example of this behavior is the direct conversion of "dry ice" into gaseous carbon dioxide, with no intermediate liquid phase at sufficiently low temperatures. Helium is unique in remaining a liquid even at absolute zero unless considerable pressure is applied. The boiling point of helium 3 (*bottom*) is about 25 percent lower than that of helium 4 (*middle*), and the freezing pressure is about 25 percent higher. Helium 3 is distinguished by having a point of minimum pressure on its melting curve; at temperatures below that of the minimum the solidification of liquid helium 3 at a fixed pressure requires the application of heat (in contrast to most substances, where heat must be removed). Superfluid phases of helium are not shown here; they are found in a very narrow region at extreme left (*see illustration on page 57*).

tures. In a superconducting metal electric current flows without any discernible loss of energy, much as a superfluid flows without friction through small pores.

Since electrons are fermions, superconductivity cannot be explained by a direct analogy with the superfluid behavior of helium 4; for electrons Bose-Einstein condensation is impossible. A fundamental characterization of the similarities and differences between the superfluidity of electrons and of helium 4 became available in 1956 with the pairing theory of John Bardeen, Leon N. Cooper and J. Robert Schrieffer. Their theory of superconductivity is based on a peculiar feature of the force between conduction electrons in a metal. In a vacuum two electrons repel each other because they carry electrostatic charges of the same polarity. In the interior of a metal, however, the force between electrons may have an attractive component generated through an intermediate interaction of the electrons with the positively charged metal ions.

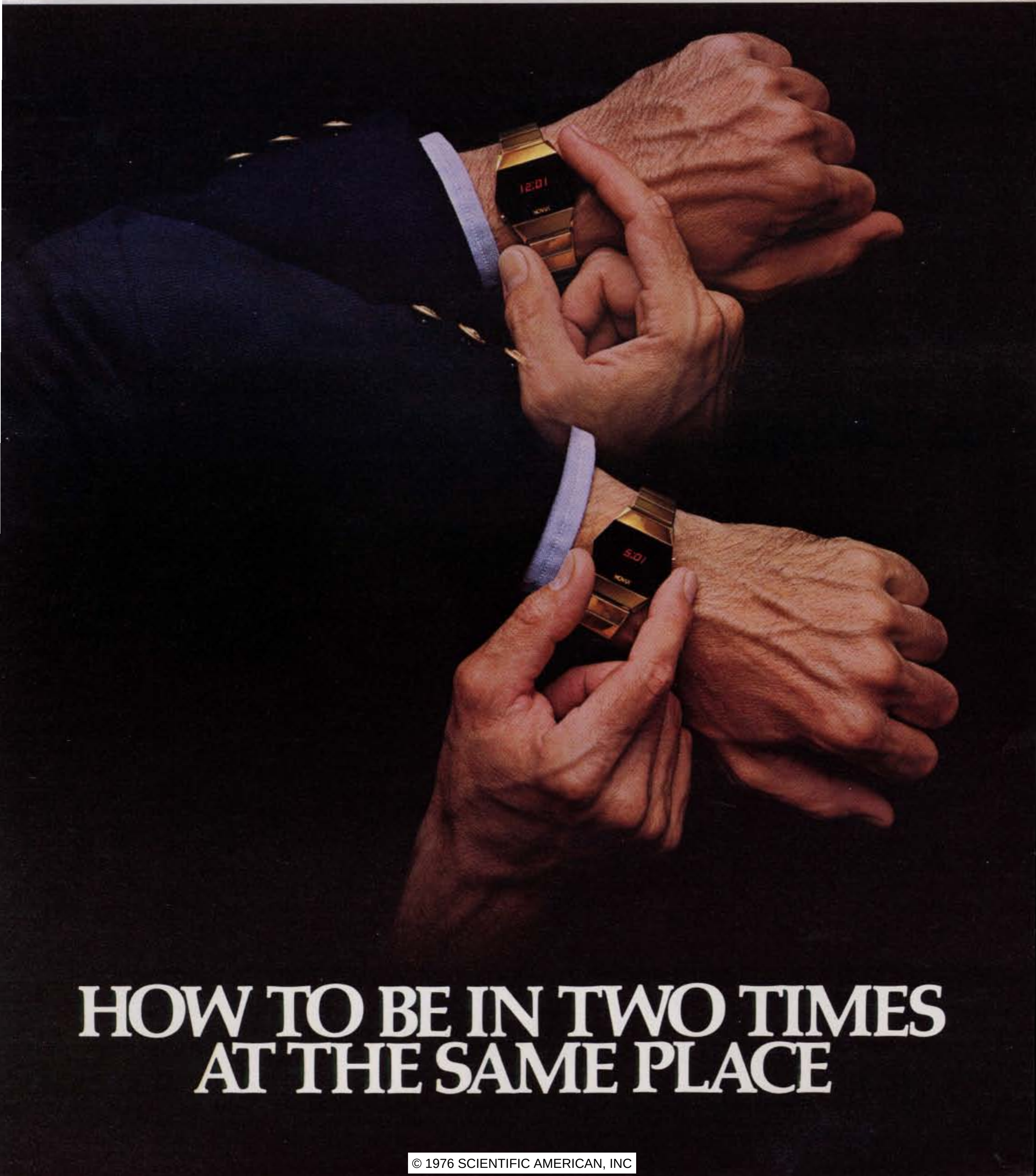
This attractive force between conduction electrons is quite weak, but at low enough temperatures it can lead to the formation of bound pairs of electrons. Indeed, the pairing theory showed that a system of fermions can form such bound pairs no matter how weak the attractive force; reducing the magnitude of the force merely increases the distance between the electrons making up a pair and lowers the temperature at which the pairs first appear.

The electron pairs produced in this way are all in the same quantum-mechanical state: they are Bose-Einstein condensed. This might appear to contradict the rule that fermions cannot undergo Bose-Einstein condensation. The condensed entities in a superconductor, however, are not single electrons but bound electron pairs. These pairs, being composed of two fermions, are bosons.

Pairing in Helium 3

The Bose-Einstein condensation of pairs of conduction electrons leads to superconductivity for reasons quite similar to those relating the superfluidity of helium 4 to the condensation of its atoms. There are, however, some striking differences between the two kinds of condensation. For one thing, the condensed entities in a superconductor (the electron pairs) can only exist when they *are* condensed, whereas helium-4 atoms exist in both the normal fluid and the superfluid. Furthermore, because the binding force between the electrons is weak the pairs are quite large. Indeed, individual separate pairs cannot exist at all: they overlap one another, the centers of mass of millions of other pairs lying within the interior of any given pair.

The electron-pair theory of super-


HOW TO BE IN TWO TIMES
AT THE SAME PLACE

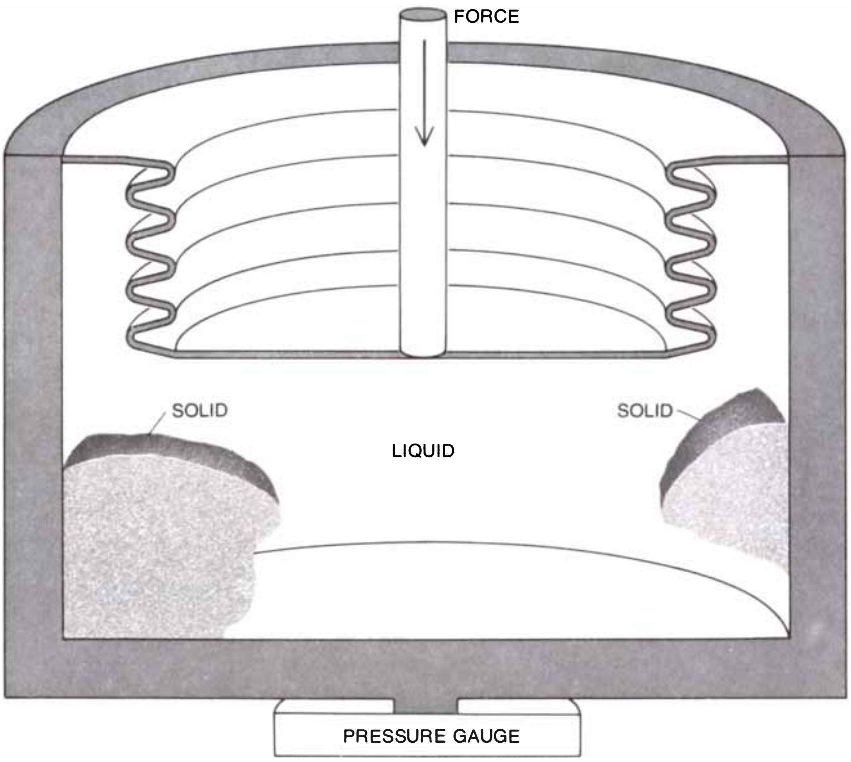
conductivity immediately suggested the possibility of analogous phenomena in helium 3. Like electrons, helium-3 atoms are fermions, and they exert a weak attractive force on one another. This force, the van der Waals force, is common to all neutral atoms, and it is responsible in the first place for the condensation of the gas into the liquid phase. The existence of an attractive force implies that at some low temperature helium-3 atoms should form bound pairs similar to the pairs of electrons in a superconductor and should acquire corresponding superfluid properties.

Although the pairing theory of superconductivity predicted that a superfluid phase of helium 3 should exist, it turned out to be extremely difficult to make reliable calculations of the temperature at which such a superfluid would first appear. Experimental searches for superfluidity in helium 3 were dependent on the development of new methods for achieving lower temperatures. Indeed, some of the most important advances in cryogenic techniques at ultralow temperatures have been by-products of the search itself. As new refrigeration techniques were devised, theoretically predicted transition temperatures were several times found to be too high, and by the mid-1960's, when some of the more pessimistic calculations were indicating that superfluidity would occur only at about a millionth of a degree above absolute zero, the search for superfluidity largely ceased.

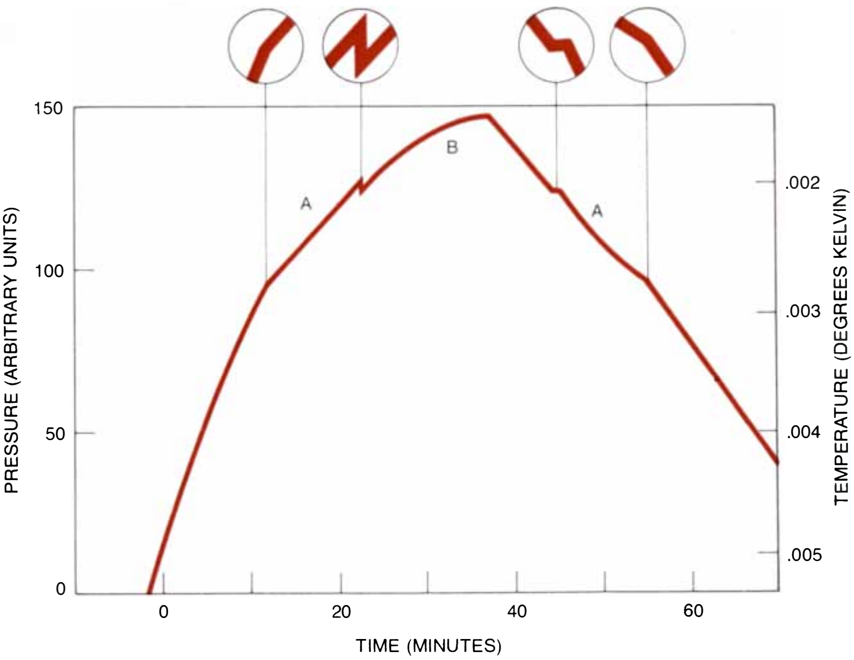
When the transition was finally discovered in 1971, it was found during an investigation (at high pressure) of the magnetic properties of solid helium 3. The discovery was made at Cornell University by Douglas D. Osheroff, Robert C. Richardson and one of us (Lee). Liquid helium 3 was present in the experimental apparatus, but only as a technical ingredient in a refrigeration scheme. This method, known as compressional cooling, is based on the fact that when a mixture of liquid and solid helium 3 is compressed, some of the liquid is converted into a solid and the temperature of the mixture drops. The superfluid transition in helium 3 was first observed at a temperature of .0027 degrees above absolute zero, which is about 1,000 times colder than the superfluid transition temperature of helium 4. It is also, however, 1,000 times higher than the most pessimistic theoretical predictions of the mid-1960's.

In the original Cornell experiment the volume of a cell containing solid and liquid helium 3 was reduced at a constant rate while the pressure inside the cell was continuously measured. The first hint of the superfluid transition was a slight but abrupt change in the rate at which the pressure increased.

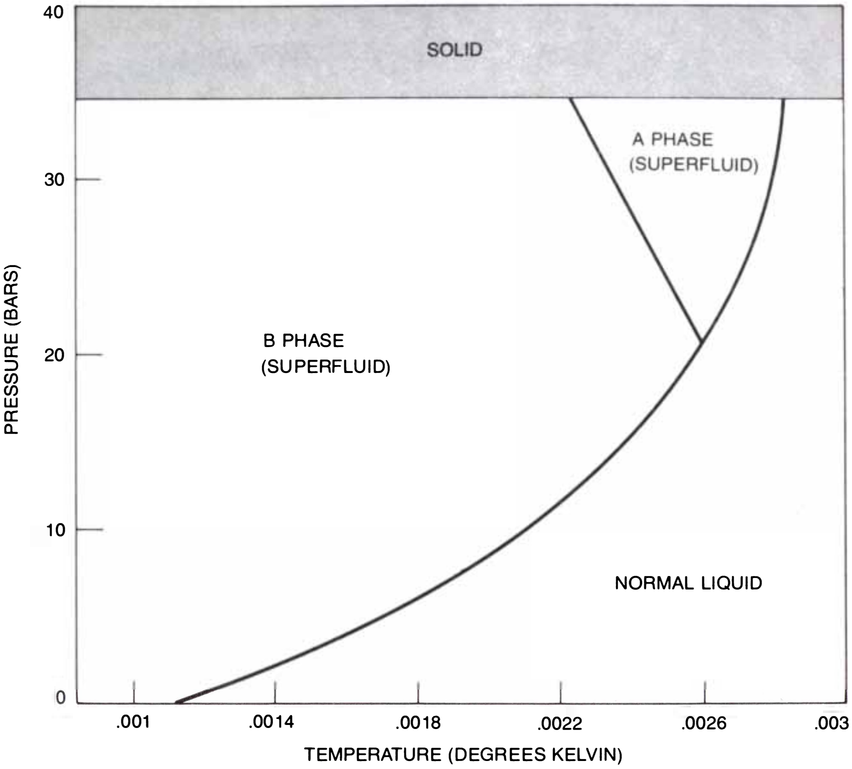
The change in the rate of pressurization of helium 3 was an intriguing anomaly and was originally interpreted as a



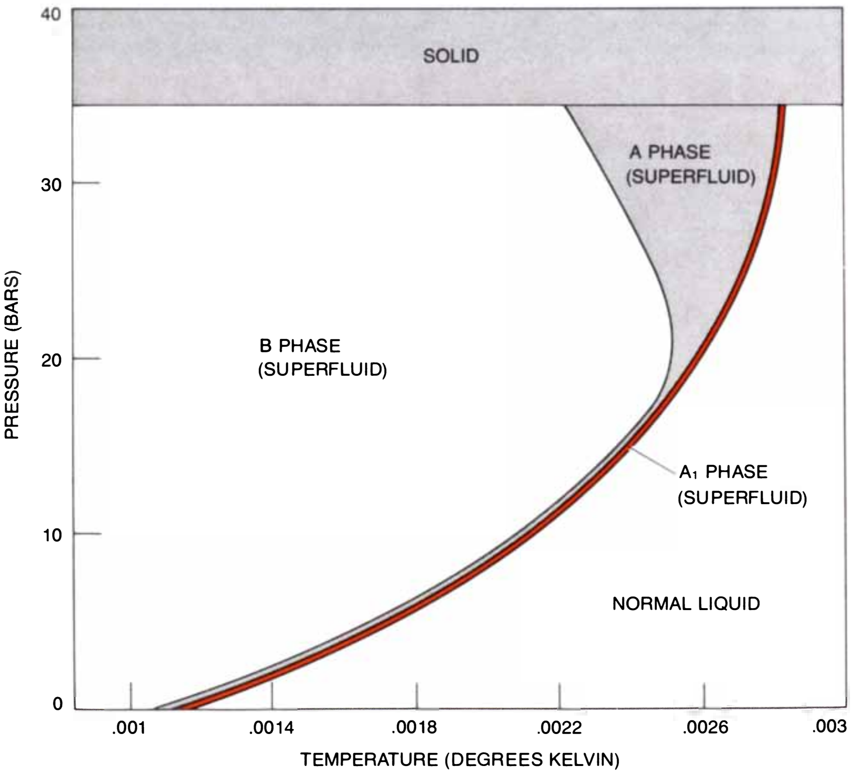
COMPRESSIONAL COOLING achieves extremely low temperatures by exploiting the fact that helium 3 absorbs heat when it freezes. The apparatus is first cooled by an external refrigerator to a temperature of .02 degree Kelvin, well below the minimum point on the melting curve. Then pressure is applied to a chamber containing both liquid and solid helium 3. As the pressure increases, more solid helium crystallizes, absorbing heat from the liquid and further cooling both phases. The superfluid phases of helium 3 were discovered in an experiment employing this method of refrigeration. Anomalous pressure behavior that signaled superfluid transition in the liquid was monitored with a sensitive pressure gauge at bottom of chamber.



FIRST EVIDENCE OF TRANSITIONS to superfluid phases in helium 3 appeared as small changes in the rate of cooling and warming in a compressional cooling cell like the one illustrated at the top of the page. The graph records the pressure in the cell (*scale at left*) as its volume was first reduced at a uniform rate, then expanded. From the pressures it is possible to calculate the equivalent temperatures (*scale at right*). Small discontinuities represent transitions from normal liquid to *A* phase to *B* phase, then a return through *A* phase to normal liquid.



DETAILED PHASE DIAGRAM of helium 3 (the plane of zero magnetic field in the illustration on page 57) displays existence of superfluids close to absolute zero. In absence of magnetic field there are just two superfluid phases, *A* and *B*, which differ in magnetic and mechanical properties. In absence of external magnetic field *A* phase exists only at elevated pressure.



MAGNETIC FIELD alters the helium-3 phase diagram. In an external field the *A* transition is split into two transitions by the appearance of a new superfluid phase, A_1. In a magnetic field both *A* and A_1 phases may extend within a narrow region of diagram all the way to zero pressure, and it is not possible to go directly from the normal liquid to the *B* phase of the superfluid. These phase-transition lines correspond to the intersections in the illustration on page 57 of a plane parallel to the P-T plane with the surfaces that separate the superfluid phases.

clue that a predicted magnetic transition was taking place within the solid helium 3 in the cell. Additional information about the effect was sought by a standard technique for investigating magnetic phenomena: nuclear-magnetic-resonance spectroscopy. The basis of this procedure is that a suitably applied external magnetic field can exert a twisting force on the orientation of a magnetic atomic nucleus, just as magnetic forces can turn a compass needle. Since all magnetic nuclei also spin like gyroscopes, however, they respond to such twisting forces with the complicated precessional motion characteristic of a spinning top. If the applied field has the right frequency, the induced motion can result in the emission of a radio-frequency signal, from which various features of the nuclear magnetism and spin can be inferred.

Liquid of Fermion Pairs

These magnetic-resonance measurements revealed that the pressure anomaly is accompanied by a striking change in magnetic properties: below the temperature of the anomaly there developed an enormous shift in the frequency of the signal broadcast by the helium-3 nuclei. This shift was far too large to be explained by any conventional theories of resonance spectroscopy. Furthermore, the shift was found to be taking place not in the characteristic signal emitted by the helium-3 atoms in the solid phase: it was unambiguously associated with the signal coming from the liquid.

The discovery of strange behavior in liquid helium 3, whatever the details, was widely regarded as evidence of the long-sought superfluid phase. A little more than a year after the discovery Anthony J. Leggett of the University of Sussex constructed a theory that accounted for the observed magnetic anomalies and predicted a number of new magnetic phenomena, many of which have since been observed. Leggett's work combined the theory of nuclear magnetic resonance with the theory describing the pairing of particles in an electrically neutral liquid of fermions. Its success convinced almost everyone (except, for a time, Leggett himself) that the new states of liquid helium 3 were indeed superfluids based on the pairing of helium-3 atoms.

The later discovery of more traditional nonmagnetic manifestations of superfluidity came almost as an anticlimax. The first indications of unusual flow properties were detected in 1973 in the laboratory of Olli V. Lounasmaa at the Helsinki University of Technology. More direct evidence of superfluid properties was obtained the following year in the laboratory of John C. Wheatley at the University of California at San Diego and in the laboratory of John D.

SCIENCE/SCOPE

The world's first all-weather, day-and-night attack system for aircraft has been ordered for the Navy's A-6E Intruder. The TRAM (Target Recognition and Attack Multisensor) System, built by Hughes, is the only attack system that successfully integrates a forward-looking infrared (FLIR) sensor, a laser designator-ranger, a laser receiver, and a precision-stabilized turret. The FLIR is the first one designed with a continuous optical-zoom capability. Because the FLIR forms an image from heat radiated by objects in view, it can operate as well in total darkness as in daylight and can also "see" through bad weather. A ship can be seen on the blackest of nights or an oil depot can be spotted on land with the amount of fuel clearly visible because of temperature differences. TRAM can deliver a variety of laser-guided and conventional weapons.

Detection and identification of tactical-size targets in any weather, day or night, has been a major goal of the US Air Force. This goal has been achieved by the development of real-time Synthetic Aperture Radar (SAR), made possible through new digital signal-processing technology. The Hughes-built APG-63 radar, with its basic digital signal processing and coherent-frequency technology, will provide a SAR capability with the inclusion of programmable signal processing. Not only are smaller tactical targets visible, but also SAR detects mobile targets, cues forward-looking infrared and electro-optical sensors, and allows precise navigation.

Hughes has many immediate openings for engineers and scientists in several areas. Electro-optics, optomechanics, and infrared, experienced in advanced adaptive optical systems, optical design & analysis, electromagnetics & electro-optical properties, solid-state physics, advanced IR imaging, systems design, MOS/bipolar circuit design . . . Laser device development, experienced in sensor/digital pattern recognition, laser alignment-control systems . . . Programming, experienced in airborne avionics, satellite ground stations, automatic test, telemetry, graphics, commercial applications. US citizenship required. Please send resume to: Professional Employment, Hughes Aircraft Company, 11940 West Jefferson Blvd., Culver City, California 90230.

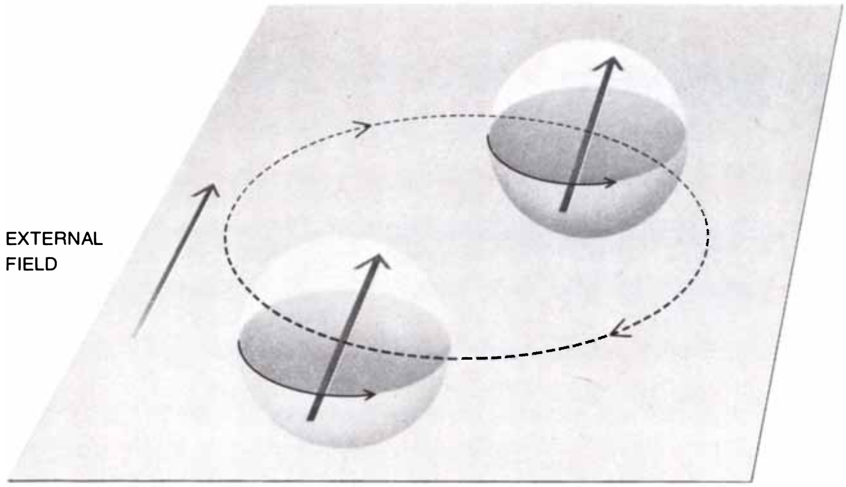
The famous sound of Morse code's dah-dit may be phasing out for the maritime industry. This is because two communications satellites are in synchronous orbit over the Atlantic and Pacific oceans. These maritime satellites, built by Hughes, are owned and operated by a consortium of carriers headed by COMSAT General Corporation. Called Marisat, the satellites are currently relaying high-quality voice, telex, facsimile, and data over both oceans for the international maritime industry. Marisat also serves the US Navy for fleet communications.

A third satellite, for Navy use and commercial backup, was placed in synchronous orbit over the Indian Ocean last October. Four-foot-diameter ship antennas allow ships to make instant contact with home port or to be reached instantly by ship telephone. Ships can also reach other ships via the system's ground stations for telex messages.

Creating a new world with electronics

HUGHES

HUGHES AIRCRAFT COMPANY



PAIR STRUCTURE in the A_1 phase of helium 3 is the simplest to describe of the pair structures in the three superfluid phases of the isotope. The elementary nuclear magnets associated with the pair of atoms are oriented so that the net magnetism of the pair lies along the direction of magnetic field. Members of pair rotate around each other in a plane containing the field.

Reppy at Cornell. In these experiments a chamber was so tightly packed with material that the interstitial spaces were exceedingly small. Liquid helium 3, forced into the tiny interstices in the chamber, was found to be completely immobilized above the transition temperature. Below the transition temperature, however, unmistakable evidence was observed that liquid was sloshing freely through the chamber. Only after the publication of these experiments in 1974 was the discovery sanctified by the appearance of a new index category: "Superfluid helium 3." By then, however, no one was surprised.

The Most Super Superfluid

From the time superfluid helium 3 was discovered it has been apparent that it is an even stranger substance than superfluid helium 4 or superconductors. The very first experiments revealed not one superfluid transition but two. They took place at .0027 and .0021 degrees K. when the pressure was 34 atmospheres. The two new phases that appear as the liquid is cooled through these temperatures have been named ^{3}He-A and ^{3}He-B. When the cooling is done in a magnetic field, still another phase, ^{3}He-A_1, appears in a narrow range of temperatures between the A phase and the normal liquid. Thus in a small region of the phase diagram helium 3 exists in five distinct phases: the solid, the normal liquid and three kinds of superfluid. The multiplicity of distinct superfluid phases in helium 3 and several other properties of the liquid set it apart not only from ordinary liquids but also from helium 4 and superconductors.

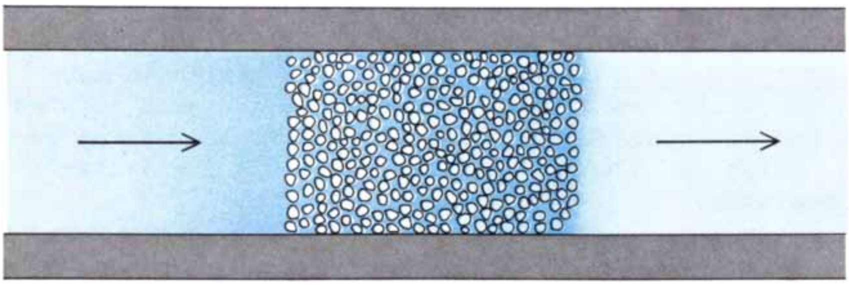
When helium 4 is compared with what we now know about superfluid helium 3, it appears to be a rather humdrum superfluid. Since helium-4 atoms have no spin and no magnetism, the superfluid they form is magnetically inert. Furthermore, the spatial structure of the helium-4 atom is the least interesting possible: it is a perfect sphere, devoid of any distinguishing features and hence incapable of favoring one direction or orientation over any other. Because of its high degree of internal symmetry the helium-4 atom is rather like the fictitious point particle of the textbooks. Except under conditions so extreme as to squash it out of its symmetrical shape, nothing can be said about a helium-4 atom other than where it is or how fast it is going. This absence of internal structure in the atom limits the kinds of phenomena that can take place in the superfluid phase; the only quantum-mechanical behavior revealed on a macroscopic scale in superfluid helium 4 is that relating to the motion of matter from place to place.

In principle a superconductor might be a more interesting superfluid, since electrons do have spin and the accompanying magnetism. In all known superconductors, however, the two electrons in a pair are oriented with their magnetic poles pointing in opposite directions. As a result the magnetic fields of the electrons cancel and the pairs are as inert magnetically as helium-4 atoms. Furthermore, like helium-4 atoms, the electron pairs in all known superconductors are as devoid of structure as the spherical electron cloud surrounding a helium atom.

Helium 3 is the only superfluid in which the condensed objects have an internal structure. One underlying reason for this structure is that in helium 3 the nuclear magnetic poles of the two atoms forming a pair are aligned in the same direction. Rather than canceling each other the magnetic fields reinforce, so that the pairs are themselves magnetic.

That helium-3 nuclei might pair in this way was anticipated more than a decade before the superfluid phases were discovered, although it was impossible to predict with assurance whether the atoms would prefer the magnetic configuration or the nonmagnetic one. That the pairing is in the more interesting magnetic form was established by nuclear-magnetic-resonance measurements made soon after the discovery. The magnetic-resonance effects could be elegantly accounted for in terms of the precession of axes characterizing the magnetic orientation of the pair. In addition the existence of more than a single superfluid phase followed from general quantum laws specifying the distinct possible configurations (or quantum states) available to an object made up of two fermions with similarly directed magnetic poles.

The net magnetism of the pairs in helium 3 has further consequences. Since the nuclear magnets of both members of the pair are similarly directed, the pairs in superfluid helium 3 cannot have the symmetry characteristic of electron pairs in a superconductor. If the two atoms were distributed about the center of mass with perfect spherical symmetry, then they would be the same in all respects, in violation of the rule that two fermions cannot occupy precisely the same state. (The electrons forming the nonmagnetic pairs in a superconductor are allowed to move around each other



FRICTIONLESS FLOW OF HELIUM 3 provides convincing evidence that the new phases of the liquid are in fact superfluids. Powder is packed tightly into a tube, making it nearly impervious to fluid flow above the superfluid transition. In the superfluid phase, however, some of the liquid flows freely through the powder. In practice the experiment is performed with an oscillating current of superfluid, which thus moves back and forth through the powder.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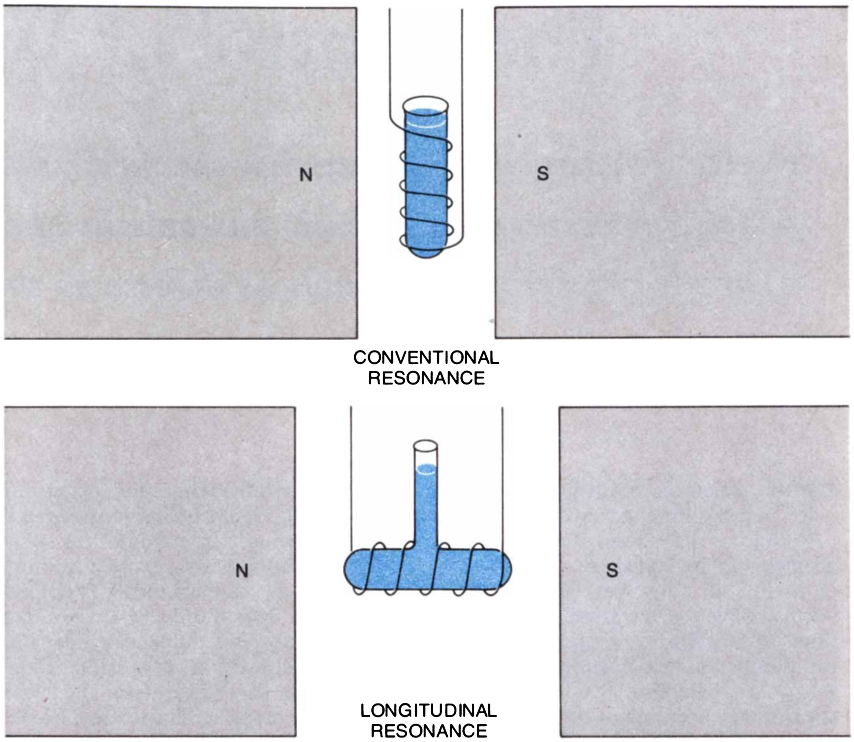
with perfect spherical symmetry because their internal magnets are oppositely directed, thereby meeting the requirement that two fermions not be alike in all respects.)

The different superfluid phases of helium 3 can be given detailed characterization in terms of this internal structure of the condensed pairs. The simplest of the phases is the A_1 phase, which exists only in a narrow range of temperatures just below the transition temperature when the fluid is exposed to a magnetic field. The nuclear spins and magnetic axes of all the pairs in the A_1 phase are aligned with each other and with the external field. (It is not yet known, however, whether they are along the field or opposed to it.) Furthermore, the two members of every pair rotate around each other in a single plane parallel to the applied field.

The A and B phases, which do not require an external field to stabilize them, involve more complicated kinds of motion. Both the magnetic axis of the pair and the axis associated with its asymmetrical shape can be oriented in three possible ways, determined by well-established quantum laws. The A and B phases are characterized by various combinations, or "superpositions," of these configurations, whose quantum-mechanical descriptions defy simple translation into classical language.



NUCLEAR MAGNETIC RESONANCE is usually carried out by studying the response of a system to a magnetic signal from a radio-frequency coil whose axis is perpendicular to an applied steady magnetic field. When helium 3 is studied by this technique, it reveals a frequency shift that is far too large to be explained by theories of conventional resonance in normal systems. The types of pairing believed to characterize the *A* and *B* superfluids, however, can produce a shift of the observed size. Pairing theories also predict that the nuclear-magnetic-resonance signals can be observed with coil oriented not perpendicular to applied steady field but parallel to it. This unusual type of signal has now been observed in both *A* and *B* phases.

Other Properties

Because of the internal structure of the pairs superfluid helium 3 has many striking properties that cannot be observed in the other superfluids. One example is the anisotropy of superfluid helium 3. Since all the pairs of atoms in the superfluid are in the same state, their asymmetrical shape is expressed in properties of the fluid as a whole. If a direction is defined by the imposition of a magnetic field, many properties of the fluid are found to depend on direction with respect to the field. For example, the rate of attenuation of sound in the liquid and the rate of superfluid flow depend on whether they are measured parallel to such a field or perpendicular to it. The dependence of mechanical properties on the direction of an applied magnetic field is commonly observed in many solids. Similar anisotropies are also observed in the esoteric liquids known as liquid crystals. What makes superfluid helium 3 unique is that in all other cases the external field interacts directly with the electrons of the atoms making up the medium. These electrons in turn are directly responsible for the mechanical properties affected by the field. In helium 3, however, the magnetic field interacts only with the tiny nuclear magnets buried deep in the interior of the atoms. That altering the direction of the nuclear magnets could have an effect on anything as gross as the attenuation of sound was unheard of before the discovery of superfluid helium 3. This is a direct manifestation of the delicate correlations, within each pair, of the two axes describing the magnetism and the spatial asymmetry.

The most intensively studied of the macroscopic quantum effects of helium 3 are those directly associated with nuclear magnetism. The signals emitted on magnetic stimulation of the superfluid phases bear little relation to patterns recorded with any other substance. We have already mentioned the anomalously large shift in the magnetic-resonance signal, observed in the earliest experiments. Each of the three phases has its own characteristic pattern of shifts, some of them (called longitudinal resonances) arising in configurations in which the conventional resonance theory predicts no signal at all. Perhaps the most impressive of these longitudinal effects arises when the strength of a static applied magnetic field is suddenly changed. When this is done in ordinary materials, the induced magnetization of the entire material somewhat sluggishly follows along, slowly subsiding to the new value appropriate to the new field strength. In superfluid helium 3 the magnetism responds to such a change in a lively oscillatory manner.

Another prediction, which is yet to be tested, is that the most stable configuration of the A phase in a stationary container should be one in which the liquid forever rotates. Superconductors and superfluid helium 4 have similar states, but they are never the most stable ones, and they can in principle decay into nonrotating configurations.

These examples are only fragments of the growing list of observed and predicted properties of the new superfluid phases of helium 3. These new superfluids have generated intense interest among physicists, in part because of the opportunities they afford to see quantum mechanics at work, as it were, in a bottle. By presenting modes of superfluid behavior substantially more general than anything available in helium 4 or superconductors, they are also forcing low-temperature physicists to reexamine and extend the theories evolved over a 50-year span to account for the behavior of pre-1971 superfluids. This kind of process can be physics at its best. At the very least it will lead to a deeper understanding of the general phenomena of superfluidity and superconductivity. And the hope has even been voiced that the effort to explain the nature of superfluid helium 3 could lead to further insight into the well-established but still profoundly mysterious structure of the quantum theory itself.