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The Effects of Spin in Gases

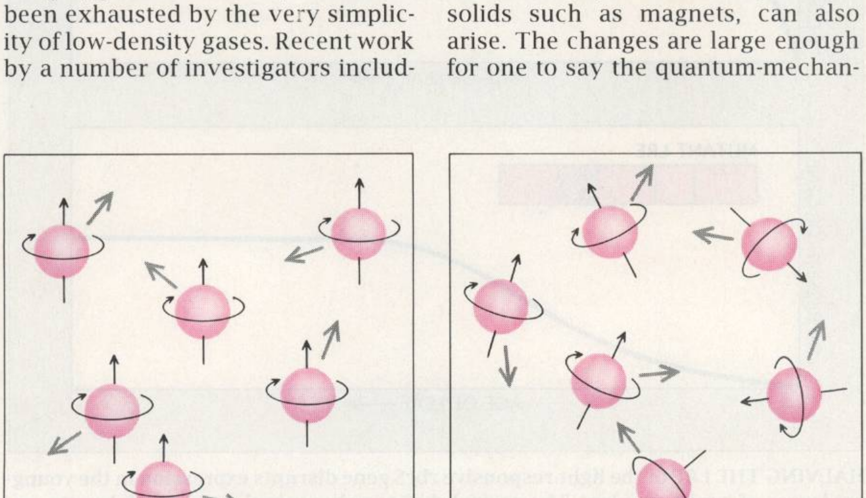
The nucleus of an atom can have a spin, somewhat like a tiny top. How can that spin, which is isolated from the outside world, dramatically change the properties of a gas, such as its ability to conduct heat?

by Franck Laloë and Jack H. Freed

Low-density gases, in which atoms are separated by large distances, have long provided an enjoyable playground for physicists. Much of the enjoyment comes from the simplicity of the medium; since the atoms collide only occasionally with one another, a theoretical understanding of the gases' macroscopic properties is easily attained. A significant fraction of the current understanding, in fact, comes from contributions made late in the 19th century by James Clerk Maxwell and Ludwig Boltzmann. In contrast, many of the properties of liquids and solids—which consist of large numbers of closely spaced, simultaneously interacting particles—continued to be mysterious until the development of the quantum theory in the early part of the 20th century, and explanations of some of the properties still elude theorists.

One might suppose the pleasure of the playground would by now have been exhausted by the very simplicity of low-density gases. Recent work by a number of investigators including us shows that this is not the case; low-density gases continue to serve up a rich variety of phenomena as well as counterintuitive surprises. In particular, the macroscopic properties of a gas composed of individual hydrogen or helium atoms can under special circumstances be changed dramatically by quantum-mechanical effects.

According to quantum theory, the nucleus of an atom behaves in a way similar to a rotating top, which has angular momentum about its axis of rotation; that is, the nucleus has spin, known more precisely as spin angular momentum. If the atoms of a gas are spin-polarized, so that their nuclei all have their spins pointing in the same direction, the viscosity of the gas can be changed enormously and so can its ability to conduct heat. Quantum-mechanical correlations among the nuclei called spin waves, which up to now had been observed only in certain liquids and solids such as magnets, can also arise. The changes are large enough for one to say the quantum-mechanical effects have caused the gas to take on entirely new properties.



GAS OF ATOMS is said to be spin-polarized when the atomic nuclei have their spins, or spin angular momenta, aligned in the same direction (*left*). Here the spins are depicted pointing "up." When the gas is unpolarized, the spins point in all directions (*right*).

In a certain sense it is amazing to think that polarizing the nuclear spins can have any effect on the macroscopic properties of the gas, since the nuclear spins are so weakly coupled to the outside world. Yet the observations are in full agreement with theory. Moreover, because spin-polarized gases are still fairly simple systems, they can be understood in terms of precise calculations made from fundamental principles, something that is still not possible to do in the case of liquids and solids.

Our work has involved two kinds of gases: atomic hydrogen and helium 3 (^{3}He). Atomic hydrogen, of course, consists of a single electron bound to a nucleus made of a single proton. Hydrogen gas in nature is generally diatomic, composed of two hydrogen atoms bound together (H_2). In recent years investigators have found that they can keep hydrogen atoms from binding and thereby prepare samples of atomic hydrogen gas by exploiting the effects of spin polarization [see "The Stabilization of Atomic Hydrogen," by Isaac F. Silvera and Jook Walraven; SCIENTIFIC AMERICAN, January, 1982]. Such samples represent yet another remarkable way in which quantum-mechanical effects come into play on a macroscopic level. Exactly how the effects make themselves felt will become clear as we discuss the effects of spin in general.

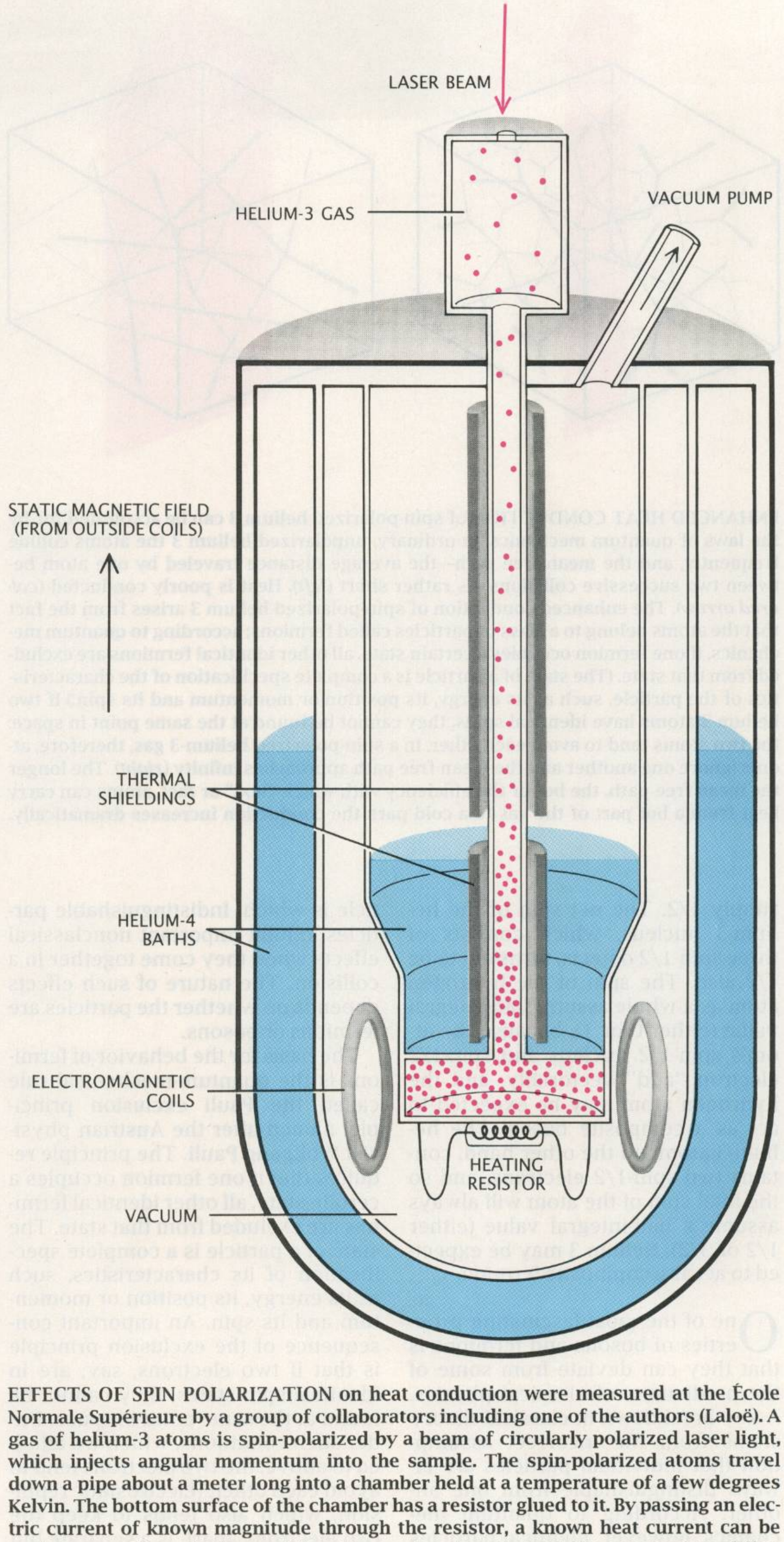
The other gas we have worked with, helium 3, has a nucleus consisting of two protons and a neutron. Two electrons are bound to the nucleus. Helium atoms are nonreactive, and so diatomic molecules of helium 3 never form. At sufficiently low temperatures—about 3.2 degrees Kelvin at atmospheric pressure—atomic helium-3 gas does liquefy. Atomic hydrogen, on the other hand, is unique among all substances in that it is expected to remain a gas even at absolute zero (zero degrees K.).

As stated by quantum theory, there are important differences in the behavior of atomic hydrogen and helium 3. Atomic hydrogen is expected to belong to a class of particles called bosons and helium 3 is expected to belong to a class of particles called fermions. The contrast between bosons and fermions is considerable. Under certain conditions that we shall elaborate on, bosons tend to come close to one another easily, whereas fermions tend to avoid one another. Such behavior is the basis of the surprising effects observed in spin-polarized gases.

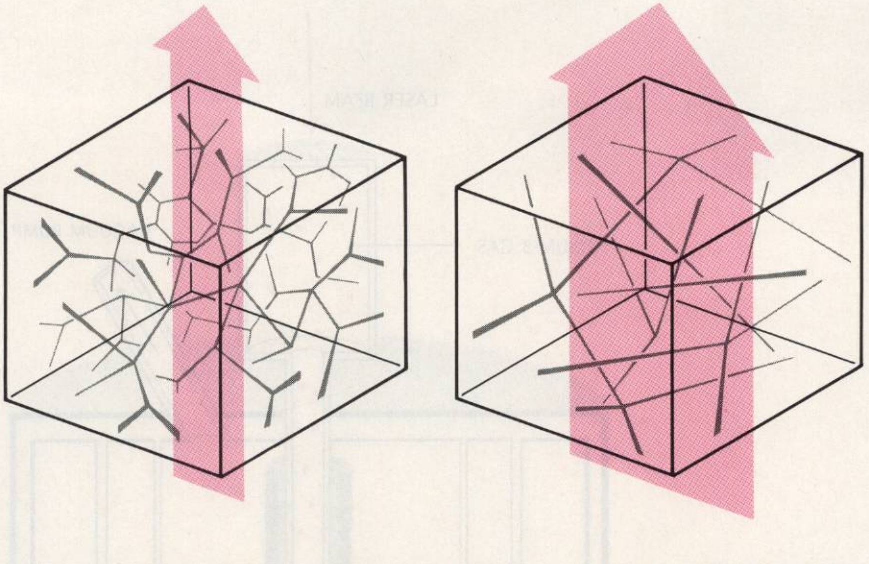
Whether a particle is a boson or a fermion depends on its spin. We have already mentioned that the nuclei of atoms have spin. It turns out that spin is an intrinsic property of every particle. Since every atom is a composite entity consisting of a nucleus and one or more electrons, it will in general have a composite spin.

The spin of a particle is somewhat like the spin of a ball, but there are important differences. The direction of the spin of a ball is given by the rule that if the fingers of the right hand curl in the same sense as the spin, the right thumb points in the direction of the spin. A quantum particle has spin, but the particle cannot be thought of as actually rotating or spinning in space. Also, unlike the spin of a ball, which can take on any angular momentum, the spin of an atom or a subatomic particle is quantized: the magnitude of the spin can take on only integer or half-integer values of the fundamental unit of angular momentum called Planck's constant. The proton, the neutron and the electron, for instance, have a spin of 1/2. The photon, or quantum of electromagnetic radiation, has a spin of 1. A particle that has half-integer values of spin, such as 1/2, 3/2, 5/2 and so on, is called a fermion, after the Italian physicist Enrico Fermi. A particle that has integer values of spin, such as 0, 1, 2, 3 and so on, is called a boson, after the Indian physicist S. N. Bose.

To determine the spin of a composite entity such as a nucleus or an atom, one must take the so-called vector sum of the spins of its components. (A vector is a quantity that has both a magnitude and a direction.) Since the nucleus of a hydrogen atom consists of a single proton, its spin is



EFFECTS OF SPIN POLARIZATION on heat conduction were measured at the École Normale Supérieure by a group of collaborators including one of the authors (Laloë). A gas of helium-3 atoms is spin-polarized by a beam of circularly polarized laser light, which injects angular momentum into the sample. The spin-polarized atoms travel down a pipe about a meter long into a chamber held at a temperature of a few degrees Kelvin. The bottom surface of the chamber has a resistor glued to it. By passing an electric current of known magnitude through the resistor, a known heat current can be made to pass through the gas. When the gas is spin-polarized, the temperature difference between the top and bottom surfaces is less than when the gas is unpolarized; spin-polarized helium 3 conducts heat better than unpolarized helium 3. The electromagnetic coils on each side of the chamber are employed to deliver a quick pulse of oscillating magnetic field to destroy the polarization for comparative measurements.



ENHANCED HEAT CONDUCTION of spin-polarized helium 3 can be accounted for by the laws of quantum mechanics. In ordinary, unpolarized helium 3 the atoms collide frequently, and the mean free path—the average distance traveled by one atom between two successive collisions—is rather short (*left*). Heat is poorly conducted (*colored arrow*). The enhanced conduction of spin-polarized helium 3 arises from the fact that the atoms belong to a class of particles called fermions; according to quantum mechanics, if one fermion occupies a certain state, all other identical fermions are excluded from that state. (The state of a particle is a complete specification of the characteristics of the particle, such as its energy, its position or momentum and its spin.) If two helium-3 atoms have identical spins, they cannot be found at the same point in space: the two atoms tend to avoid each other. In a spin-polarized helium-3 gas, therefore, atoms ignore one another and the mean free path approaches infinity (*right*). The longer the mean free path, the better the efficiency with which "hot," or fast, atoms can carry heat from a hot part of the gas to a cold part: the conduction increases dramatically.

simply 1/2. The net spin of the helium-3 nucleus, which consists of three spin-1/2 objects, turns out to be 1/2 also. The spin of the hydrogen atom as a whole assumes an integral value (either 0 or 1), because the atom's spin-1/2 nucleus and spin-1/2 electron "add" vectorially, and the hydrogen atom may be expected to act as a composite boson. The helium-3 atom, on the other hand, contains two spin-1/2 electrons, and so the total spin of the atom will always assume a half-integral value (either 1/2 or 3/2). Helium 3 may be expected to act as a composite fermion.

One of the most fascinating properties of bosons and fermions is that they can deviate from some of the predictions of classical physics. A key breakdown in classical theory stems from the incorrect assumption that individual particles are always distinguishable from one another. According to quantum mechanics, however, identical particles that have identical spins are in fact indistinguishable: no measurement can be made to determine which particle is which. Indistinguishable particles exhibit important nonclassical effects when they come together in a collision. The nature of such effects depends on whether the particles are fermions or bosons.

The basis for the behavior of fermions is the quantum-mechanical rule called the Pauli exclusion principle, named after the Austrian physicist Wolfgang Pauli. The principle requires that if one fermion occupies a certain state, all other identical fermions are excluded from that state. The state of a particle is a complete specification of its characteristics, such as its energy, its position or momentum and its spin. An important consequence of the exclusion principle is that if two electrons, say, are in identical spin states, they cannot be found at the same point in space. Under such conditions, which we alluded to above, the two electrons tend to avoid each other. (Electrostatic repulsion, which also tends to keep the two electrons apart, is a separate but important consideration.) It is the exclusion principle, applied to the electrons of atoms, that gives rise to the properties of all the elements, each with its own distinct and stable electronic configuration.

Let us now clarify what we mean by indistinguishability in a collision between two fermions. One can in principle observe the respective paths of the two fermions as they approach each other. The collision alters their directions, and one can then observe their paths as they recede from each other. If both fermions are in the same spin state, one cannot distinguish which fermion is which. If, however, they are in different spin states, they can (at least in principle) be distinguished by measuring the direction of their spins. This would enable one to determine the complete path of each fermion, that is, one would know which fermion is which. (The same statement applies to a collision between two bosons.) The tendency of two indistinguishable fermions to avoid each other is known to influence the way they interact during a collision.

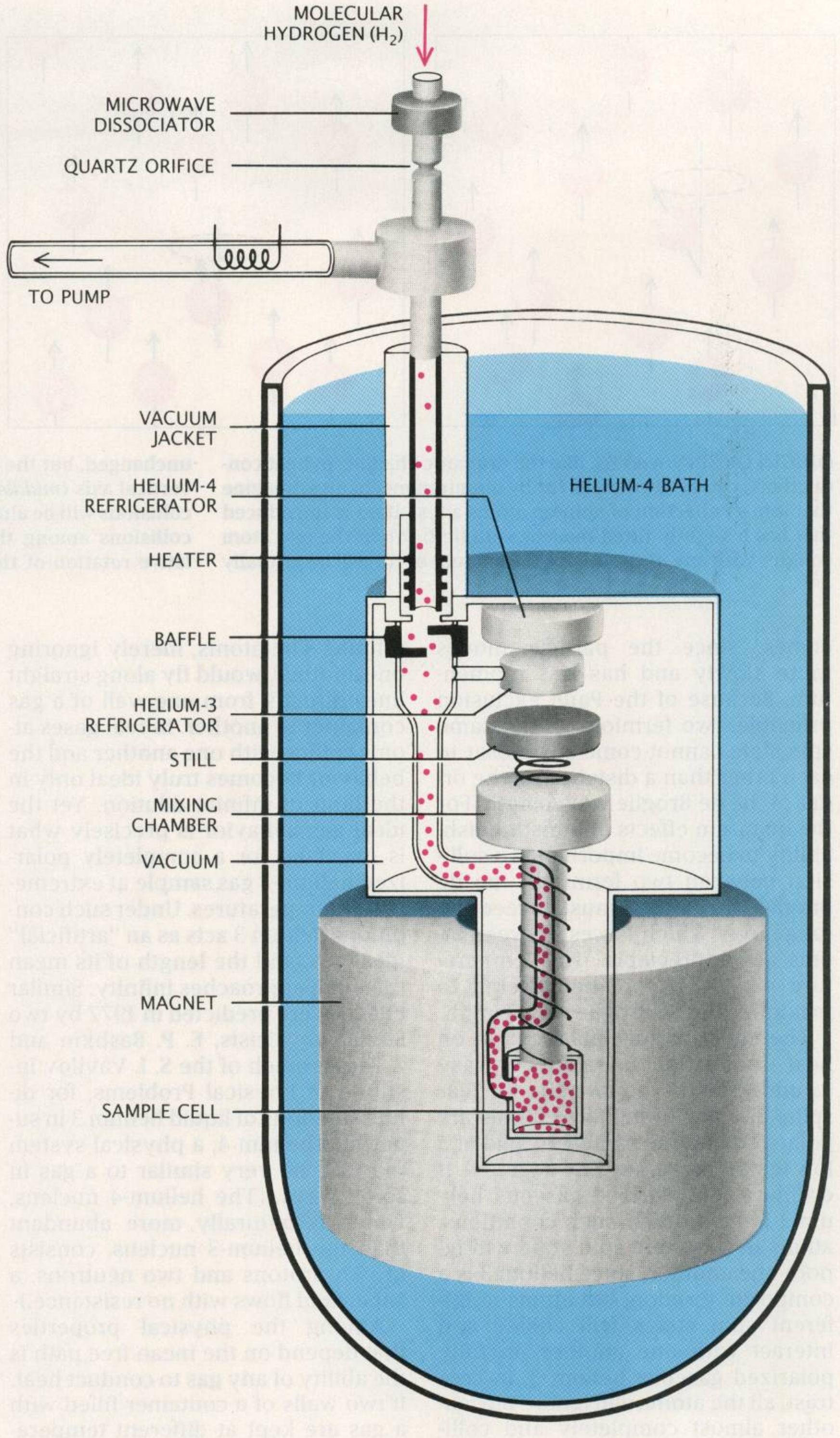
Bosons, on the other hand, do not follow the Pauli exclusion principle. There is no limit to the number of bosons that can occupy the same quantum state. If two simple bosons, such as photons, have identical spins—and are therefore indistinguishable—they tend to come close to each other more readily than two distinguishable particles would. Composite bosons such as hydrogen atoms with identical electron spins will exhibit a similar effect when their nuclear spins are the same.

The exclusion principle can be exploited to keep individual atoms of hydrogen from combining to form molecular hydrogen (H_2) when they collide. Actually, although the hydrogen atom is a composite boson, its constituent proton and electron are fermions and therefore obey the exclusion principle. In ordinary, unpolarized gaseous hydrogen the spins of the electrons of the atoms point in all directions in a random manner. (In an applied magnetic field the spins can point in only one of two directions, either "up" or "down.") Two electrons that have the same spin state are indistinguishable and will tend to avoid each other. If each electron is part of a hydrogen atom, this would prevent the formation of a chemical bond between them. If the electron spins point in different directions, however, they are distinguishable and no quantum principle keeps them from being in the same place at the same time. If each electron is part of a hydrogen atom, it is energetically more favorable for the two atoms to bind together than for them to remain apart. Molecular hydrogen forms.

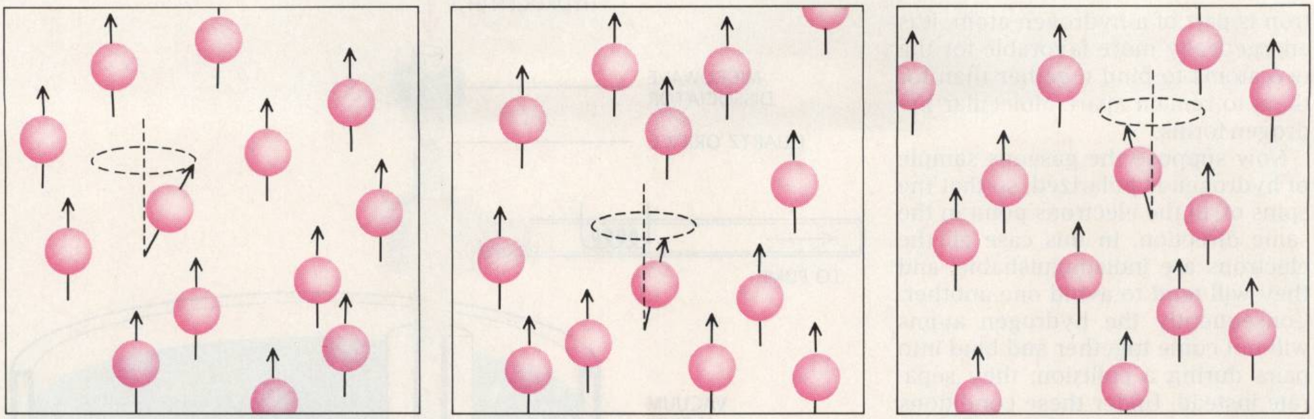
Now suppose the gaseous sample of hydrogen is polarized, so that the spins of all the electrons point in the same direction. In this case all the electrons are indistinguishable, and they will tend to avoid one another. Consequently the hydrogen atoms will not come together and bind into pairs during a collision; they separate instead. Under these conditions atomic hydrogen is stable and molecular hydrogen will not form. In recent years a number of laboratories around the world have produced stabilized atomic hydrogen gas by spin-polarizing the electrons.

In our work we have addressed the question of what happens when the nuclear spins of atomic hydrogen and helium 3 are polarized. (The hydrogen atoms are "doubly polarized": the electron and the nucleus are both polarized. In helium 3 in its ground state one does not need to be concerned about polarizing the electrons: each pair of electrons in an atom are in opposite spin states, yielding a composite electron spin of zero.) The effects of polarizing the nuclear spins are remarkable, particularly in the light of the fact that the tiny magnetic top associated with each nuclear spin is almost indifferent to the environment surrounding the atom. The reason the nuclear spin is isolated from the outside world is that the magnetic force associated with it is roughly 1,000 times weaker than the magnetic force associated with the spin of each electron of the atom. Of course, the effects of nuclear spin polarization do not come from the magnetic forces associated with the nuclear spins. Rather, the dramatic changes in macroscopic properties are built-in consequences of the quantum-mechanical description of identical particles.

An important aspect of all our work is that it has been done in very low temperatures, no more than a few degrees above absolute zero. Low temperatures are necessary because of the wave-particle duality of matter and radiation. A particle has associated with it a certain wavelength known as the de Broglie wavelength, which is inversely proportional to the momentum of the particle. The lower the temperature is made, the longer the de Broglie wavelength be-



ANOTHER SPIN PHENOMENON, called spin waves, has been observed at Cornell University by a group of collaborators including one of the authors (Freed). A spin wave in a polarized gas is a collective oscillatory mode of the nuclear spins, so that the spins precess, or rotate, about the average direction of polarization at a frequency that depends on the amount of polarization. To study the waves, hydrogen molecules (H_2) are first dissociated into hydrogen atoms by bombardment with microwave radiation. The atoms are then cooled and spin-polarized and allowed to fill a small chamber, which is immersed in a strong magnetic field. The spin waves are induced by a pulsed nuclear-magnetic-resonance (NMR) technique, in which a short pulse of radio waves is used to tilt the nuclear spins at some small angle from their initial direction, and so afterward they precess around the static magnetic field at a rate proportional to the strength of the field. The rotating spins create a rotating magnetization that is transverse, or perpendicular, to the main direction of polarization. This transverse magnetization induces a voltage that is amplified, detected and analyzed by its frequency spectrum.



ORIGIN OF SPIN WAVES, like the dramatic changes in heat conductivity, can be accounted for by quantum mechanics. Imagine that into a collection of spin-up atoms a test atom is introduced that has a slightly tilted nuclear spin (*left*). When the test atom collides with any of the atoms, the amount of tilt will be virtually unchanged, but the test spin will be rotated slightly around the vertical axis (*middle*). The effect on the test spin in subsequent collisions will be almost identical. As a consequence the random collisions among the atoms will eventually produce a cumulative rotation of the test spin around the vertical axis (*right*).

comes, since the particle moves more slowly and has less momentum. Because of the Pauli exclusion principle, two fermions in the same spin state cannot come any closer to each other than a distance on the order of the de Broglie wavelength. For the quantum effects of indistinguishability to become important in a collision between two fermions, the de Broglie wavelength must exceed the range over which forces between atoms are appreciable. The temperature must therefore be lowered to maximize the de Broglie wavelength.

The effect of spin polarization on heat conduction is relatively easy to understand. Suppose the nuclear spins of a gas of helium-3 atoms are polarized and the sample is held at a low temperature, say one degree K. If ordinary, unpolarized gaseous helium 3 is held under such conditions, atoms in the same spin state will ignore one another, since helium 3 is a composite fermion, but atoms in different spin states will collide and interact with one another. In fully polarized gaseous helium 3, in contrast, all the atoms will ignore one another almost completely and collisions will be much less frequent. It is as if a complete nuclear polarization "switches off" any interactions among the atoms.

The switching off of atomic interactions leads to significant changes in an important physical quantity called the mean free path: the average distance traveled by one atom between two successive collisions in a gas. In an ideal gas the atoms would have no mutual interaction at all, so that their mean free path would be infinite. The atoms, merely ignoring one another, would fly along straight lines directly from one wall of a gas container to another. In real gases atoms collide with one another and the behavior becomes truly ideal only in the limit of infinite dilution. Yet the ideal gas behavior is precisely what is expected for a completely polarized helium-3 gas sample at extremely low temperatures. Under such conditions helium 3 acts as an "artificial" ideal gas, and the length of its mean free path approaches infinity. Similar effects were predicted in 1977 by two Soviet physicists, E. P. Bashkin and A. Meyerovich of the S. I. Vavilov Institute of Physical Problems, for dilute solutions of liquid helium 3 in superfluid helium 4, a physical system that can be very similar to a gas in some ways. (The helium-4 nucleus, which is naturally more abundant than the helium-3 nucleus, consists of two protons and two neutrons; a superfluid flows with no resistance.)

Among the physical properties that depend on the mean free path is the ability of any gas to conduct heat. If two walls of a container filled with a gas are kept at different temperatures, the heat flow across the system is proportional to the mean free path: the longer the mean free path, the better the efficiency with which the "hot," or fast, atoms will carry their energy from the hot wall to the cold one. Consequently a polarized gas of helium 3 at low temperatures should have a much higher heat conductivity—it would approach infinity as the mean free path approaches infinity—than its unpolarized counterpart. The viscosity of the gas should also increase for similar reasons, although the effect is not as intuitive.

The effects of spin-polarizing the nuclei of hydrogen atoms, on the other hand, should be just the opposite. The reason is that hydrogen atoms are bosons (actually composite bosons made of two fermions, remember), and that as identical particles they therefore tend to come close to one another more easily. Spin-polarizing the nuclei should make the mean free path shorter and decrease both the viscosity and the heat conduction. Even in an unpolarized sample, however, bosons are largely free to interact with one another anyway, and so the effects of polarization should be less pronounced than they are for fermions and less interesting to investigate experimentally.

The effect of spin polarization on heat conduction in gaseous helium 3 was observed and measured by a group of collaborators including Pierre-Jean Nacher, Geneviève Tastevin, Michèle Leduc, Stuart B. Crampton, David S. Betts, James M. Daniels and one of us (Laloë) at the École Normale Supérieure in Paris. It is first necessary to polarize the helium nuclei. To do so a technique called laser optical pumping was used. Optical pumping is a general method, invented in 1950 by Alfred Kastler, then at the École Normale, in which a beam of circularly polarized light (light in which the associated electric field rotates about the direction of travel) is employed to inject angular momentum into a gas of atoms and polarize their spins. Many atoms can be polarized this way, but helium raised specific difficulties that were solved in 1963 at Texas Instruments Incorporated by Forrest D. Colegrove, Laird D. Schearer and G. King Walters in an approach that was further refined by Leduc and her colleagues at the École Normale.

The second problem is to create the nuclear polarization in a cold gas, at temperatures of a few degrees Kelvin, where the quantum effects are significant. At the École Normale this was done by using a special container called a double cell. The container has two chambers: one held at room temperature, where the helium nuclei are polarized by optical pumping, and one held at a low temperature, where the measurements are made. The two parts are connected by a pipe about a meter long in which the atoms diffuse under the effect of their random thermal motion. The diffusion transfers polarization from the room-temperature cell to the cold measurement cell. To minimize the sticking and interaction of the atoms with the cold cell, the walls are coated with solid molecular hydrogen.

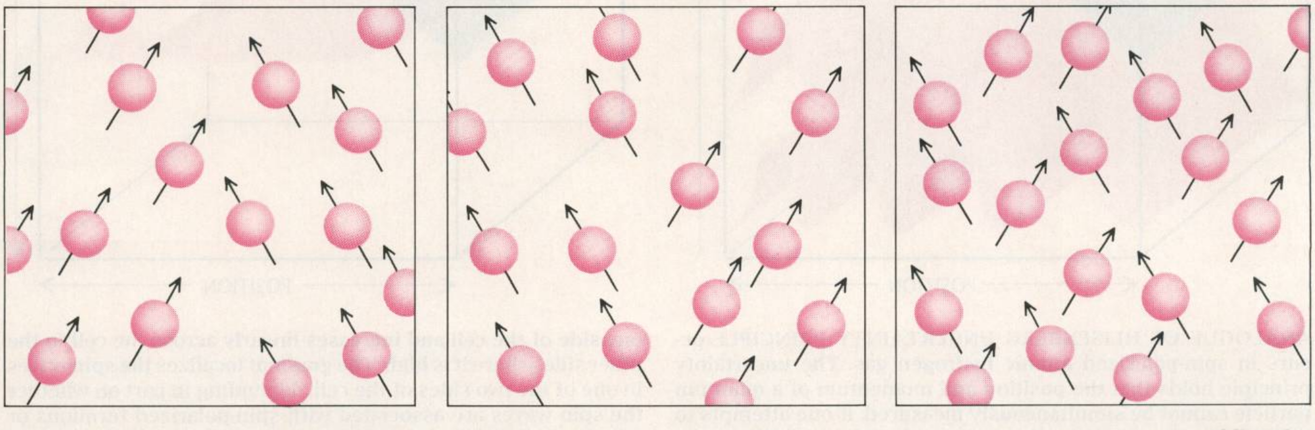
The measurement cell itself has the shape of a cylinder, about a centimeter high and a few centimeters in diameter. The upper flat surface is in contact with a helium-4 bath, which acts as a refrigerant. The temperature of the bath can be adjusted between one and four degrees K. The lower flat surface has a resistor glued to it and is in contact with a vacuum. An electric current of known magnitude passing through the resistor causes a known heat current to pass through the gas; a simple measurement of the temperature difference between the two flat plates provides a measurement of the heat-conduction coefficient of the gas.

The experiment consists of recording the temperature difference when a spin-polarized sample of helium-3 gas fills the cell and then applying an oscillating magnetic field in a quick pulse to destroy the polarization suddenly. A change of nuclear polarization does indeed trigger a macroscopic temperature change; the temperature difference between the top and the bottom of the cell is less when the gas is polarized. The observed change matches the predicted change, and the peculiar implications of quantum theory are upheld.

We have mentioned above that the quantum effects of spin-polarizing the nuclei of a gas are not limited to heat conduction. Another phenomenon was actually observed earlier: spin waves. These waves arise from the cooperative interaction of particles with spin and are perhaps best known for their role in permanent magnets. In a permanent magnet large numbers of electrons have their spin in the same direction. Since each electron spin behaves like a tiny magnet, the cumulative effect is to produce the permanent magnetization. Now suppose (with the aid of an external magnetic field if necessary) all the electrons are made to spin in the same direction, say up, except for one, which points down. This single down spin, which can be thought of as a "spin-down excitation," can propagate rapidly through the magnet: by interacting with the spins of the surrounding electrons, the spin-down excitation flip-flops its way through the magnet. Such delocalization is a simple example of a spin wave.

The origin of spin waves in a gas is somewhat different, because the atoms are not fixed; they move constantly in all directions. Moreover, the spin waves that have been observed involve the spins of atomic nuclei, which are shielded quite well from the outside world. How can occasional random collisions in a gas lead to correlations among the spins of many atoms to make spin waves possible?

The answer once again is found in the quantum behavior of identical particles. As we have mentioned, the result of a collision between two identical atoms depends on the spin directions of their nuclei, even though the forces of interaction between the two atoms have nothing to do with the nuclear spins. Suppose, for example, one introduces into a collection of identical spin-up atoms a test atom that has a nuclear spin tilted slightly with respect to all the other nuclear spins. (Such a spin can be expressed as a vector sum of a spin-up state with a small amount of spin-down character.) When the test atom collides with any of the atoms, the amount of downward tilt will remain virtually the same, but the test spin will be rotated slightly around the vertical axis. (This is a consequence of the spin-up part of the test atom's being indistinguishable in a collision with a spin-up atom, whereas the spin-down part engages in a distinguishable collision.) The effect on the test spin in subsequent collisions will

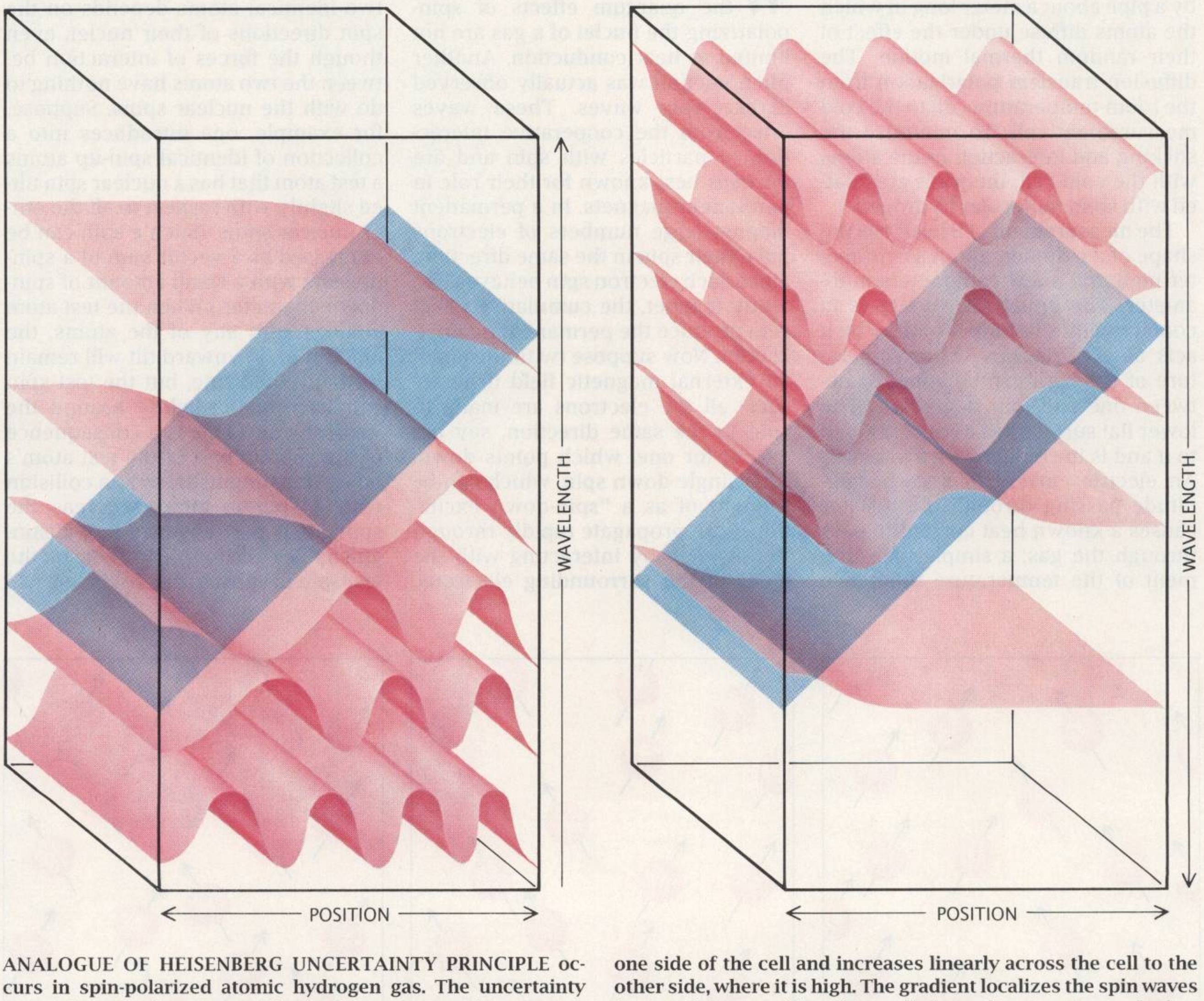


SPIN WAVES in a gaseous sample typically arise when the nuclear spins in one region of the sample are tilted differently from the nuclear spins in another (*left*). The transverse magnetization in each region can be transmitted coherently through the sample by the cumulative effect of the successive collisions of the atoms, a behavior that constitutes the spin waves (*middle*). The same random thermal motions that create the spin waves ultimately destroy them as well; the motions transfer atoms randomly from a region where the transverse magnetization points in one direction to a region where it points in another (*right*).

be almost identical, because the collisions are always with spin-up atoms, and so the random collisions among the atoms will produce an overall cumulative rotation of the test spin around the vertical axis.

Now suppose the nuclear spins in one region of a sample are tilted differently from the nuclear spins in another region. The macroscopic effect of tilting spins in one region of the sample is first to create some magnetization in a direction that is transverse, or perpendicular, to the main direction of polarization. This transverse magnetization is then transmitted coherently through the sample by the cumulative effect of the successive collisions of the atoms. The spins tend to rotate about the average direction of polarization and at a frequency that depends on the amount of polarization. Such a collective oscillatory mode in the gas is the spin wave. The more pronounced the quantum effects are, the more rapid the oscillation is.

An interesting aspect of spin waves in gases is that the same thermal motions that create the spin waves in random collisions are also responsible for destroying the waves. Typically, a gaseous sample containing spin waves will have several regions of different transverse magnetizations. The thermal motions of the atoms eventually transfer the atoms by a diffusional process from a region where the magnetization points in one direction to a region where the transverse magnetization points in another direction. In time the mixing of regions will randomize the overall transverse magnetization, so that there will be no preferential direction of the magnetization in the sample. The effectiveness with which spin waves are transmitted in a gas versus the randomization of the transverse magnetization by thermal motions is proportional to the de Broglie wave-



ANALOGUE OF HEISENBERG UNCERTAINTY PRINCIPLE occurs in spin-polarized atomic hydrogen gas. The uncertainty principle holds that the position and momentum of a quantum particle cannot be simultaneously measured: if one attempts to measure the position of a particle, the measurement itself will change the state of the particle, so that after the measurement the particle will be more localized in space. Similarly, spin waves in a measurement cell are localized by immersing the cell in a constant magnetic field gradient, the strength of which is low at one side of the cell and increases linearly across the cell to the other side, where it is high. The gradient localizes the spin waves in one of the two sides of the cell, depending in part on whether the spin waves are associated with spin-polarized fermions or particles called bosons. The spin waves associated with doubly spin-polarized hydrogen atoms, which act as composite bosons, should be trapped at the side that has the high field gradient (*left*). If the particles were instead to act as fermions, they would be trapped at the side that has the low field gradient (*right*).

length of the atoms and inversely proportional to the range over which the atoms interact (multiplied by the magnitude and direction of the nuclear-spin polarization).

The observation of spin waves in a gas was made at Cornell University by a group of investigators including Burgess R. Johnson, John S. Denker, Nicholas P. Bigelow, Laurent P. Levy, David M. Lee and one of us (Freed). The work involved atomic hydrogen gas, because it has the least mass, yielding the largest de Broglie wavelength. This maximizes the effectiveness with which spin waves are transmitted as compared with the diffusional randomization. The gas is generated by dissociating molecular hydrogen with microwave radiation. The individual atoms of hydrogen are then made to travel through a tube lined with Teflon, the nonstick coating found on many frying pans, and subsequently in a low-temperature section of the tube, a film of superfluid helium 4. The Teflon and liquid-helium coatings are employed to minimize the recombination of the hydrogen atoms back to molecular hydrogen on the walls of the tube, since atomic hydrogen does not stick as well to these coatings as it does to other materials.

The atomic hydrogen gas then enters a cell, which has a volume of .3 cubic centimeter, in which the temperature is extremely low—only a few tenths of a degree above absolute zero. The sample cell is immersed in a high magnetic field, which attracts atoms that have electron spins antiparallel to the field (down spins) and repels atoms that have electron spins parallel to the field (up spins). As a consequence the cell contains only atoms that have spin-down electrons. In other words, the electrons in the gaseous sample are spin-polarized. As we discussed above, molecular hydrogen will not form in such a gas. The atomic hydrogen gas is thereby made stable.

Now, the nuclear spins of the hydrogen atoms can be either parallel or antiparallel with respect to the spins of the polarized electrons. Atoms with nuclear spins that are antiparallel—that is, up—become slightly depolarized, and they recombine with one another and deposit on the walls of the cell, so that a layer of solid molecular hydrogen gradually forms. After a few minutes the cell contains only doubly polarized atoms: atoms with nuclear spins that are parallel to the electron spins. (Both are antiparallel to the magnetic field.) The effect was first shown by Thomas J. Greytak and Daniel Kleppner of the Massachusetts Institute of Technology.

The polarized atomic nuclei have been made to exhibit spin waves by a pulsed nuclear-magnetic-resonance (NMR) technique developed by the Cornell workers. In this technique a short pulse of radio waves is used to tilt the nuclear spins at some small angle from their initial direction, so that afterward they precess, or rotate, around the static magnetic field at a rate that is proportional to the strength of the field. The rotating spins create a rotating transverse magnetization, which induces a voltage that is amplified, detected and then analyzed in terms of its frequency spectrum.

An important feature of the Cornell experiment is that a constant magnetic field gradient is applied to the static magnetic field: the combined field strength is low at one side of the sample cell and increases linearly across the cell to the other end, which has a high value. As a result nuclear spins in different parts of the sample cell precess around the field at different rates. Normally the range of different rotation frequencies of the nuclear spins in the different parts of the sample cell would produce a frequency spectrum that consists of a broad resonance line. Such a characteristic spectrum is in fact exploited in other NMR applications to obtain spatial images of materials, and it is the basis of the magnetic-resonance-imaging (MRI) technique employed by hospitals. But the unique feature of the Cornell experiment is that superposed on the broad resonance line is a series of prominent, narrow resonance peaks. The peaks correspond to the spin-wave modes in the sample cell.

The magnetic field gradient also produces another remarkable effect. The effect is an analogue of the Heisenberg uncertainty principle, which states that both the position and the momentum of a quantum particle cannot be determined simultaneously. A consequence of the uncertainty principle is that if one attempts to measure the position of a particle, the very act of the measurement itself will change the state of the particle in such a way that after the measurement the particle will be more localized in space.

Similarly, the spin waves in the sample cell are localized in space by applying the field gradient to determine their location. In the absence of the field gradient the waves are delocalized, but in the presence of the gradient the spin-wave modes are localized in one of the two sides of the sample cell. The field gradient both traps the spin waves and allows them to be imaged, that is, detected by the NMR technique.

The spin waves are trapped either at the side of the cell that has the low combined magnetic field strength or the side that has the high value. One of the factors in making the determination is whether the atoms in the gaseous sample act as fermions or as bosons. According to theory, much of which was developed at Cornell by Levy and Andrei E. Ruckenstein, the spin waves associated with the doubly spin-polarized hydrogen atoms, which generally act as composite bosons, should be trapped at the side that has the higher field strength. The experimental evidence supports the theory and dramatically confirms the fact that under the proper conditions hydrogen atoms act as composite bosons.

As a final note, the existence of spin waves has also been observed in gaseous helium 3. The work was done by the collaboration at the École Normale. Although the spin waves are not as spectacular as those in atomic hydrogen, their existence is just as significant. The observations are in good agreement with the theoretical predictions of Claire Lhuillier of the École Normale and one of us (Laloë).

As more experiments are done with spin-polarized gases, it is quite probable that the techniques developed in working with the gases will spawn practical applications. Already, for instance, some of the techniques have been successfully exploited by a number of groups to build a new low-temperature hydrogen-atom maser, which could prove to be an extremely accurate atomic clock. Nuclear physicists are working on the use of spin-polarized helium 3 as targets for particle collisions. In the near future, however, it seems likely the real significance of spin-polarized gases is that they will continue to offer the opportunity to investigate, from first principles, a wide range of quantum phenomena including interesting hydrodynamic effects.