

have further discussions with our European partners."

Victor Weisskopf of MIT (a former CERN director), in his keynote address to the ICFA meeting in Japan (to be delivered by video recording), was to say that "an early drive at CERN to attempt the highest possible hadron energies in the LEP tunnel would jeopardize the chances to get the SSC in the US. American efforts towards an

SSC would make it much harder to get Western European governments to finance the use of the LEP tunnel for hadron collisions, in addition to the exploitation of lepton collisions by LEP I and LEP II....

"It is the duty of the community to come to a mutually acceptable solution. It is an issue of scientific responsibility versus scientific greed. But it is also an issue of wise policy towards the govern-

ments who pay the bill. We certainly will lose the support we have received in the past if it appears that different parts of the world community are trying to outpace each other and are no longer cooperating in the planning and construction of future accelerators, with mutual help and assistance. The danger is all the more acute since, even under the best conditions, this support is not assured." —GBL

Nuclear spin waves seen in dilute polarized gases

Spin waves in crystalline ferromagnets have been known since the 1950s. It is less obvious that such collective propagating modes of oscillating magnetization can be excited in liquids. But spin waves in degenerate Fermi liquids were predicted as early as 1958 and eventually seen in such Fermi-liquid systems as liquid helium-3 and the conduction electrons of paramagnetic metals.

In all of these systems the deBroglie wavelength of the constituents is at least comparable to the distance between nearest neighbors; there is sufficient overlap between wavefunctions so that the symmetrization required by the quantum statistics of identical particles is clearly significant. The quantum exchange interaction generated by identical-particle symmetrization is known to play a crucial role in the propagation of spin waves. It is not surprising, therefore, that the possibility of spin waves in non-degenerate dilute gases—where neighbors are much farther apart than their deBroglie wavelengths—was overlooked until quite recently.

Two years ago Claire Lhuillier and Franck Laloë at the École Normale Supérieure in Paris made a theoretical case¹ for the possibility of observing nuclear spin waves in dilute, nondegenerate gases of spin-polarized atomic hydrogen, deuterium and helium-3. Even in such rarefied systems, they pointed out, identical-particle symmetrization requires that the collisions by which nuclear spin perturbations diffuse through the gas have to depend on the relative spin orientations of the colliding particles, even if the interaction has no explicit spin dependence. This would introduce a precession of the spins of the colliding particles, giving rise in successive collisions to the coherent propagation of a perturbation introduced into the spin-polarized gas. It is not necessary that the deBroglie wavelength be as large as the mean interatomic spacing in the gas, they calculated; it need only be larger than the effective sizes of the atoms themselves. E. P. Bashkin at the Institute for Physical Problems in Moscow

made a similar prediction² at about the same time.

The existence of spin waves in a very dilute gas of spin-polarized atomic hydrogen has now been clearly demonstrated³ by David Lee, Jack Freed and their colleagues at Cornell. The striking pattern of resonant nmr peaks found in their experiment turns out to agree well with the spectrum of standing spin-wave modes predicted⁴ by Laurent Lévy and Andrei Ruckenstein (both now at Bell Labs), who reformulated the Lhuillier-Laloë theory in the quasiparticle language previously employed for degenerate Fermi systems, and emphasizing the essential identity of the physics of spin waves in the three seemingly disparate cases: ferromagnets, degenerate quantum liquids and dilute gases.

When he heard of the Cornell result, Laloë wrote to Lee: "As an ex-atomic physicist, I'm pleased to see that dilute systems—not just condensed matter—exhibit interesting quantum modes." There has been considerable skepticism, he pointed out, as to the possibility of seeing spin waves in a nondegenerate Boltzmann gas. "I'm pleased that you've now shown these arguments were pessimistic." In recent months, Laloë's experimental group in Paris has found⁵ less dramatic, but nonetheless convincing evidence for spin waves in spin-polarized helium-3 gas, and Wilfred Gully and William Mullin at the University of Massachusetts have made similar observations⁶ in a nondegenerate, dilute solution of helium-3 in liquid helium-4.

Spin-polarized atomic hydrogen is a particularly interesting system in which to look for spin waves. Whereas hydrogen atoms of opposite spin quickly combine to form molecular H_2 , hydrogen atoms of parallel spin experience only very weak mutual attraction. This, together with its low atomic mass, renders spin-polarized atomic hydrogen (usually written $H\uparrow$) the only material that is expected to remain a gas even at absolute zero temperature. Thus, as one increases its mean deBroglie wavelength $\lambda = h(2\pi/mkT)^{1/2}$ by lowering the temperature T ,

one can easily satisfy the Lhuillier-Laloë condition $\lambda \gg d$, where d is the atomic size, long before degeneracy effects become important.

As the deBroglie wavelength approaches the interparticle spacing at high density or low temperature, a fluid becomes degenerate. In a degenerate fluid of fermions, all quantum states well below the Fermi surface are occupied and hence inaccessible to newcomers. A degenerate fluid of bosons such as spin-polarized atomic hydrogen, on the other hand, would ultimately undergo Bose condensation to a single macroscopic quantum state. The effort to observe such Bose condensation has in fact been the principal impetus for the recent development of techniques to stabilize $H\uparrow$ at ever lower temperatures and higher densities (PHYSICS TODAY, June 1980, page 18).

At temperatures around 0.5 K and densities on the order of 10^{16} atoms/cm³, the $H\uparrow$ sample in which the Cornell group observed spin waves is still very far from Bose condensation. The thermal deBroglie wavelength (about 20 Å) is more than an order of magnitude smaller than the mean interatomic spacing, but it is significantly larger than the hard-core scattering size of the colliding atoms. The Cornell sample is held in a somewhat nonuniform magnetic field with a mean value of 77 kilogauss. In such a strong field at low temperatures only the two lowest-energy hyperfine states of atomic hydrogen are initially occupied. In the lowest-lying state ($|a\rangle$), the electron and nuclear spins are antiparallel, while the slightly more energetic $|b\rangle$ state has its electron and nuclear spins aligned. In both states, the great preponderance of electron spins are aligned opposite to the externally imposed magnetic field, but $|a\rangle$ has a small admixture of electron spins opposite to the majority. It is almost exclusively through this component that hydrogen atoms can combine into molecular H_2 . Thus, as the newly formed molecular hydrogen is removed from the sample by adsorption on the helium-4-coated walls, one is eventually left with nothing but the $|b\rangle$ state of

atomic hydrogen. That is to say, all the electron and nuclear spins are polarized opposite to the external field. (The relaxation process by which some $|b\rangle$ states eventually revert to $|a\rangle$ is much slower than the molecular recombination process that removes the $|a\rangle$ states from the sample.) The nuclear spins have effectively been "chemically polarized."

The spin waves observed in H_1 are of course collective, oscillatory perturbations of the nuclear spin magnetization. Because the magnetic moments and hence the energy level spacings of the electron spins are a thousand times greater than those of the proton, we may assume that the electron spin directions are fixed by the external field and ignore them.

To understand the microscopic origin of the spin rotations that lead to spin waves in a polarized gas, consider what happens when one introduces a single atom whose nuclear spin is tilted at some angle from the polarization direction. If we assume that the scattering interaction between colliding atoms has no intrinsic spin dependence, a classical treatment tells us that nothing happens. The lone misaligned atom will simply preserve the direction of its idiosyncratic tilt through repeated collisions. One might well expect that a classical treatment would be adequate. At the low gas densities considered here, classical Boltzmann statistics are appropriate, but it turns out that in collisions between identical atoms one cannot ignore the quantum effects of symmetrization.

The one tilted atom of our *Gedankenexperiment* can be thought of as a linear superposition of two spin states: one with its nuclear spin aligned with all the others and a second state antiparallel to the rest. In a collision, the scattering amplitude of the latter state can be treated as a collision between distinguishable particles—labeled by their different nuclear spin orientations. But the scattering amplitude involving the aligned state must be symmetrized; $f(\theta)$ must be replaced by $f(\theta) \pm f(\pi - \theta)$, and if $\lambda \gg d$, the cross term in $|f|^2$ cannot be ignored.

The result is that in repeated collisions the two spin basic states of the lone tilted atom will experience different time evolutions even though the interatomic potentials have no explicit spin dependence, and the expectation value of the transverse spin component will precess about the external field direction at a rate determined by the difference between the symmetrized and the unsymmetrized scattering amplitude.

Invoking the language of ferromagnetic and Fermi-liquid spin waves, one attributes this precession of the tilted spin about the direction of general alignment to an effective local "molec-

ular magnetic field" due to the identical-particle exchange interaction that generates the spin dependence. In the ferromagnetic metallic lattice, however, this local molecular field is a permanent fixture, generated by multi-particle electron-exchange interactions so strong that the system is spontaneously magnetized—an example of spontaneous symmetry breaking. In the dilute H_1 or helium-3 gas, where only two-body nuclear exchange interactions are involved, the exchange forces are quite weak, and it requires an imposed external field to bring about the necessary breaking of rotational symmetry. The effective local molecular fields exist only during the brief moments of collision. Spin waves occur as a cumulative, coherent consequence of repeated collisions, in each of which the two colliding atoms precess about the sum of their spins. Long-term coherence is made possible by the broken symmetry—the great majority of the nuclei are aligned in one preferred direction. In a degenerate Fermi liquid, the effectiveness of the local molecular field in generating spin waves is attributed to the fact that competing conventional collision processes are "blocked" because the final states into which particles would ordinarily scatter are all occupied. It is the absence of this blocking effect in a dilute, non-degenerate gas that engendered much of the skepticism Laloë spoke of.

A macroscopic description of spin waves yields a wave equation that describes the collective propagation of a local perturbation of the magnetization (magnetic moment per unit volume) as a continuous vector field variable. In a ferromagnet, the derivation of the wave equation is fairly straightforward. The exchange interaction generates a local energy perturbation proportional to the square of the gradient of the perturbed magnetization. Thus the Laplacian of the locally non-uniform magnetization becomes a local field about which the magnetization will precess. One gets a wave equation relating the spatial and temporal disturbances of the ground-state magnetization, generating propagating normal modes with temporal frequencies proportional to the strength of the exchange interaction and the inverse square of the wavelength. In the long-wavelength limit, damping is negligible, assuring the existence of propagating spin waves.

In a liquid or gas, damping becomes a more serious issue because the energy dissipation in an external magnetic field is due to the actual motion of the particles through the fluid. Adapting the quasiparticle description of Fermi liquids developed by Anthony Leggett (now at the University of Illinois) and Michael Rice (now at Xerox) in 1968 to

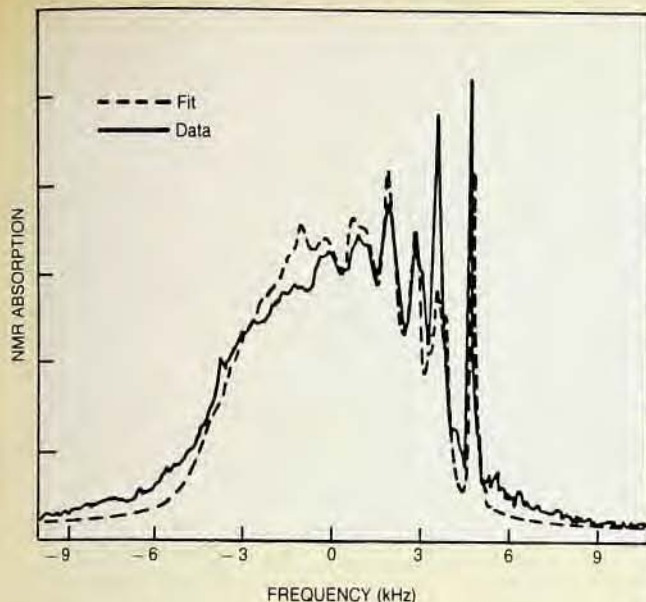
non-degenerate gases, Lévy and Ruckenstein point out that in the latter case, unlike ferromagnetism, the magnetization cannot precess about the local molecular field. In a dilute, spin-polarized gas it turns out to be the precession of the spin current (the flux of the spin density) about the local molecular field that offers the possibility of spin waves. If the Larmor period of this precession is much shorter than the spin-current relaxation time in the gas, the spin current can no longer follow its driving magnetization gradient. Thus it acquires a reactive component normal to the magnetization gradient and one gets propagating oscillations of the magnetization.

The wave equation one obtains for a small transverse perturbation of the magnetization in a dilute, spin-polarized gas looks very much like a Schrödinger equation with a complex mass. If, however, the spin-current Larmor precession is much faster than the spin-current relaxation time (as is the case with H_1), the mass factor is predominantly real and one gets good wave-like solutions. The "potential term" in this Schrödinger-like equation is dominated by the gradient of the imposed magnetic field.

In the Cornell experiment, the deviation of the imposed 77-kilogauss magnetostatic field from uniformity was essentially a constant gradient, so that the wave equation in this case looks like a Schrödinger equation for a charged particle in a uniform electric field (Stark effect). The relatively large imposed magnetic field gradient in the Cornell experiment serves two functions: It couples the sample to the nmr pulses that serve to perturb the nuclear spins in the first place, and it makes for a more interesting standing-wave spectrum.

The H_1 sample is confined in a roughly 1-cm-wide cell inside an nmr resonator. The magnetic-field gradient serves effectively as a potential barrier off which lower-energy spin-wave excitations bounce, producing a spectrum of localized standing waves. The lowest-energy excitation is confined by the field gradient to the low-field end of the cell, with higher-energy modes extending further across the cell as the "potential barrier" permits.

The Cornell group's first inkling of spin waves in H_1 came during the investigation of spin-relaxation processes in H_1 in their nmr apparatus. In the absence of spin-wave resonances one would expect to see free-induction decay tails lasting about 100 microseconds after pulsed-nmr excitation of the nuclear spins. They found instead that the system "continued to ring forever"—that is to say, for milliseconds. This did not come as a complete surprise, because Lévy, whose theoretical work with Ruckenstein anticipated



NMR absorption spectrum measured at Cornell for spin-polarized atomic hydrogen gas exhibits striking resonant peaks, indicating standing nuclear spin-wave modes. The zero of the nmr frequency scale is the nuclear tipping frequency (1.04 GHz) in the 77-kG field of the small cryogenic cell. The data agree well with the spectrum predicted by Lévy and Ruckenstein. The imposed field gradient serves as the potential well that reflects the spin waves, strongly localizing the lowest-lying standing modes seen at the high-frequency end.

spin waves in low-density H_1 , was also a member of the Cornell experimental team. Other members of the group were Burgess Johnson, John Denker and Nickolas Bigelow.

Fourier transforming these long decay curves, the group saw the first indications of the rich standing-spin-wave spectrum excited in the H_1 cell by the nmr pulses. In the subsequent spin-wave experiments the group recorded the nmr absorption spectrum by varying the magnetostatic field so as to sweep the nuclear Larmor-precession frequency across a range around the central resonator frequency of 1042 MHz.

Superimposed on the broad nmr peak expected for a magnetostatic field gradient of 2 gauss/cm, they found a series of prominent, narrow, resonant absorption spikes corresponding to standing spin-wave modes in the cell. The lowest energy resonances, corresponding to the severest localization of the standing wave modes by the field gradient, were narrowest in frequency spread. At higher energies, where the standing waves were able to extend further and further across the cell, the resonant peaks broadened, eventually blending into the background curve. The highest, least localized modes are only weakly coupled to the resonator.

The observed spectrum of standing-wave modes turns out to be in excellent agreement with the solution of the wave equation calculated for the Cornell experimental geometry by Lévy and Ruckenstein. A nice feature of the dilute gas, in contrast to spin-waves in a degenerate Fermi liquid, is that the comparison of theory and data does not require the adjustable phenomenological parameters made necessary by the very complex multiparticle interactions of these dense systems. The H_1 experiment has also provided a new

demonstration, if indeed such was needed, that the hydrogen atoms behave like bosons. For simplicity of description, we have said that the lowest-energy standing waves are localized at the low-field end of the cell. For bosons the opposite is in fact the case. If, for some reason, the hydrogen atoms were obeying Fermi statistics, the nmr spectrum would have been the mirror image of what was in fact observed.

Other experiments. Spin-polarized hydrogen has a number of experimental advantages over other dilute systems in which one might look for spin waves. The product $\tau\omega$ of the spin-current relaxation time and its precession frequency about the molecular field is a density-independent measure of spin-wave quality; spin-wave damping decreases as $\tau\omega$ increases. Spin-polarized hydrogen turns out to have significantly higher $\tau\omega$ than does spin-polarized helium-3 gas. Furthermore, the chemical polarization that makes possible the nearly perfect alignment of hydrogen nuclei does not occur in chemically inert helium.

Nonetheless, clear, albeit less dramatic, evidence of spin waves in dilute, nondegenerate He^3 systems has now been seen by the École Normale Supérieure and University of Massachusetts groups. Using laser optical pumping at room temperature and a clever technique that transfers the polarization to a cryogenic cell, the Paris group was able to achieve 50% polarization in their gaseous He^3 sample. The magnetic field in this cell was, however, three orders of magnitude lower than that of the Cornell experiment, and its gradient is correspondingly small. The resulting weak coupling of the nmr-induced transverse magnetization to the spin waves produces a shift in the precession frequency of the transverse magnetization. The measurement of

this shift provides an experimental determination of the spin-wave quality parameter. Although it is much lower than in H_1 , the good agreement between its measured value and the theoretical calculation⁷ of $\tau\omega$ in gaseous He^3 by Lhuillier "clearly indicates the presence of spin waves," we were told by Stuart Crampton (Williams College), a member of the Paris collaboration.

Unlike the gas-phase experiments, the work of Gully and Mullin was done with a solution of He^3 in liquid He^4 . But the concentration of He^3 was so small (4 parts in 10^4) that one can think of the system as a dilute, nondegenerate gas of quasiparticles. They achieved a 30% polarization "by brute force" in an 89-kG field at 25 mK. Because of the very slow diffusion rate at this extremely low temperature, the spin waves are too localized to be detected directly. Gully and Mullin have therefore employed a spin-echo technique, which accumulates the effects of the anomalous spin-current precession over time. After an nmr tipping pulse, one lets the spin perturbation diffuse for a while before measuring the resulting rotation of the magnetization in the echo signal. By increasing the concentration of He^3 in experiments of this kind, one will presumably be able to see the smooth transition of spin-wave phenomena from the dilute, non-degenerate case to the degenerate case.

Surprisingly, although spin waves in degenerate (undiluted) liquid He^3 were predicted 26 years ago, the experimental evidence has until very recently been only indirect. The first direct observation of spin waves in liquid He^3 was reported at this year's Washington APS meeting by Donald Candella of Ohio State. "Our spectrum looks amazingly like the spin-wave modes seen at Cornell in the atomic hydrogen gas," we were told by David Edwards, leader of the Ohio State group. Isaac Silvera (Harvard) points out that in H_1 one should probably be able to see *electronic* spin waves in addition to the nuclear spin waves already found. But recent searches at the Universities of Amsterdam and British Columbia have not yet seen them. —BMS

References

1. C. Lhuillier, F. Laloë, J. Phys. (Paris) **43**, 197 (1982).
2. E. P. Bashkin, JETP Lett. **33**, 8 (1981).
3. B. Johnson, J. Denker, N. Bigelow, L. Levy, J. Freed, D. Lee, Phys. Rev. Lett. **52**, 1508 (1984).
4. L. Lévy, A. Ruckenstein, Phys. Rev. Lett. **52**, 1512 (1984).
5. P. Nacher, G. Tastevin, M. Leduc, S. Crampton, F. Laloë, J. Phys. (Paris) Lett. **45**, L441 (1981).
6. W. Gully, W. Mullin, Phys. Rev. Lett. **52**, 1810 (1984).
7. C. Lhuillier, J. Phys. (Paris) **44**, 1 (1983). □