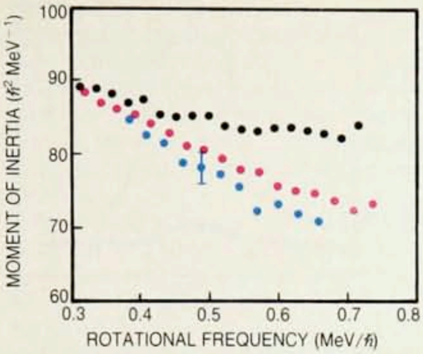

Moments of inertia have been measured for superdeformed states of Dy^{152} (black circles), Gd^{149} (red) and Gd^{148} (blue). The dynamic moment of inertia for the first of these remains fairly constant over a wide range of rotational frequencies, while the latter two are smaller and decrease with increasing frequency. The constancy of the moments of inertia for Dy^{152} suggests that this nuclear state is behaving very much like a rigid rotor. A representative error bar is given for Gd^{148}.

clei. Fission isomers fall into one of these dimples, just inside the fission barrier.

After the discovery of the fission isomers, two groups of theorists[7,8] studied nuclear deformations produced by rotations and discovered that for rotating nuclei, large deformations can also produce significant shell structure stabilization. In the case of fission, the strong Coulomb force of the heavy actinide nuclei helps to stabilize the nucleus in an elongated shape, because the protons are on average further apart in an ellipsoid. In lighter nuclei such as the rare earths, the centrifugal force plays a similar role.

While theory predicted what has now been observed in high-spin nuclei, it has not yet answered many of the questions posed by the new measurements. One challenge is to understand which parameters—such as number of valence nucleons, atomic number or mass number—determine the formation of a stable superdeformed state. Some theorists have proposed that abundances and regularities seen in the spectra of single-particle states as a function of deformation might be related to approximate symmetries of the nuclear average potential—pseudo SU(3) or pseudospin.[9]

A second challenge is to understand the dynamics of transitions among the deformed states. By what collective motion, for example, can the hot compound nucleus cool into a minimum-energy superdeformed state in a matter of femtoseconds?

The sudden transition between the prolate superdeformed states and the oblate states at a certain spin also invites explanation. In the normal states pairs of nucleons are strongly correlated. The nucleus behaves then somewhat like a superfluid, in analogy with the superconducting states in condensed matter. At high spins these pair correlations seem to disappear. This effect is reminiscent of the disappearance of superconductivity in magnetic fields, although the analogy is far from perfect. In any case, the superdeformed nuclei offer the opportunity to study these pairing correlations.

The superdeformed nuclei also offer the opportunity to study another possible type of transition—from a somewhat ordered, fluid-like behavior to a more ordered, solid-like behavior. Wladyslaw Swiatecki of Lawrence Berkeley Lab has undertaken a macroscopic analysis to deduce certain elementary physical properties of the rapidly spinning Dy^{152} nucleus directly from the small deviations of its rotational spectrum from that of a rigid rotor.[10] Swiatecki told us he is interested in exploring the transition from order to chaos in a quantum system that is predicted to be associated with a solid to fluid transition.

Others are interested in learning more about the nuclear giant dipole resonance from its possible influence on the superdeformed state. The giant dipole resonance arises when all the protons in a nucleus oscillate against all the neutrons. Its energy is inversely proportional to the length of the axis of oscillation. Therefore, in a deformed nucleus, which has at least two axes of different length, the giant dipole resonance will split. In a superdeformed nucleus, the energy of the lower component, corresponding to an oscillation along the longer axis, is further decreased. Nuclear physicists are trying to understand how this splitting might affect the population and decay of the superdeformed band.[11]

Among the more interesting predictions to emerge from the current spate of theoretical work is the suggestion made by Jerzy Dudek (Center for Nuclear Research, Strasbourg, France) and his collaborator Thomas Werner (Warsaw University) at an international conference on nuclear shapes held in Crete during the summer of 1987. They proposed that "super superdeformed" nuclei might exist, corresponding to major-minor axis ratios perhaps as large as 3:1.

—Barbara Goss Levi

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STUDIES OF NEW SUPERCONDUCTORS REVIVE OLD QUESTIONS

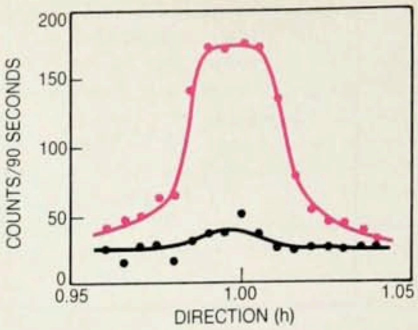
Lanthanum copper oxide, which is now regarded as the prototype for the new high-temperature superconductors, undergoes a phase transition to an antiferromagnetic state. The critical temperature for this transition, at which the magnetic moments on copper ions begin to order antiferromagnetically, depends sensitively on the oxygen concentration. Confirmation of the existence of this antiferromagnetic phase in La_2CuO_{4-y} and the determination, using neutron scattering, of the arrangement of magnetic moments in it provided definitive evidence last summer for the importance of magnetic phenomena in the new superconducting oxides. Philip Anderson (Princeton University) had proposed in January 1987 that superconductivity in La_2CuO_{4-y} doped with barium or strontium, which had been confirmed only two months earlier, arose from novel, short-range antiferromagnetic correlations between copper spins.

A team of physicists from Brookhaven National Laboratory, MIT, and the Electrical Communication Laboratories of Nippon Telephone and Telegraph Corporation now reports[1] that magnetic moments on copper ions in La_2CuO_{4-y} are correlated antiferromagnetically over large distances even at temperatures far above the Néel temperature T_N, at which the true long-range antiferromagnetic order sets in: In a single-crystal sample of La_2CuO_{4-y} with a T_N of 195 ± 5 K, the correlation length exceeds 200 Å at 300 K. The pattern of these correlations shifts rapidly in time: A pair of moments stays correlated for only 10^{-14} seconds, which is about one order of magnitude shorter than the time scale on which moments change directions randomly due to thermal fluctuations, and many orders of magnitude shorter than the time scale usually observed in antiferromagnetic systems with comparable correlation lengths.

Lanthanum copper oxide has a tetragonal structure at high temperatures, but the crystal structure changes to one of orthorhombic symmetry at a temperature between 450 K and 530 K whose precise value also depends on the oxygen concentration. The tetragonal structure consists of alternating planes of CuO_2 and LaO stacked along the tetragonal axis. In the orthorhombic phase, the CuO_2 layers become corrugated and the Cu–O bonds along the tetragonal axis tilt slightly. The La_2CuO_{4-y} samples that the Brookhaven–MIT–NTT team studied were in the orthorhombic phase. A most striking aspect of the magnetic correlations the team discovered is that they exist only in the CuO_2 layers: At any given instant, each CuO_2 layer has its own pattern of correlations, which is independent of the pattern in the layers above and below it. This two-dimensional nature of the correlations is in sharp contrast to the eventual antiferromagnetic ordering in the crystal when it is cooled, because the antiferromagnetic order below T_N extends in all three dimensions (see PHYSICS TODAY, September, page 17).

Robert Birgeneau (MIT) and Gen Shirane (Brookhaven), both of whom have used neutron scattering to study magnetic phases and phase transitions in a variety of systems over the past 20 years, told us that the magnetic behavior of La_2CuO_{4-y} is unlike any they had encountered before. The crystal structure of potassium nickel floride, whose magnetic properties Birgeneau and Shirane, among others, studied extensively in the late 1960s and early 1970s, is similar to that of tetragonal La_2CuO_{4-y}. Furthermore, spin-1 magnetic moments on Ni^{2+} in K_2NiF_4, like the spin-½ moments on Cu^{2+} in La_2CuO_{4-y}, order antiferromagnetically. The ordering is three dimensional, but above the Néel temperature (about 97 K) there are strong antiferromagnetic correlations between nickel moments in the planar NiF_2 layers of the tetragonal K_2NiF_4. Birgeneau and Shirane told us, however, that the correlations in K_2NiF_4 at temperatures above its T_N, unlike those in La_2CuO_{4-y}, can be properly described as those of a two-dimensional system approaching a critical point, or a second-order phase transition, at T_N. One manifestation of the propinquity to a critical point is that the time scale of the correlations in K_2NiF_4 grows as the critical point is approached and diverges algebraically at the critical point. This critical slowing down, so called because a system with long-lived correlations takes a long time to reach equilibrium when it is perturbed, is not observed in La_2CuO_{4-y}. "The time scale of correlations between copper moments in La_2CuO_{4-y} does not change much over a wide temperature range, but their spatial range, measured by the correlation length, decreases with increasing temperature—from about 200 Å at 300 K to about 50 Å at 500 K, in a sample with T_N of about 195 K," Birgeneau told us.

Paul Fleury, Kenneth B. Lyons and their colleagues at AT&T Bell Laboratories have determined, from inelastic scattering of light by single crystals of La_2CuO_{4-y} and $YBa_2Cu_3O_{7-y}$, the magnitude of the exchange interaction responsible for the correlations observed in neutron scattering.[2] "We have observed magnetic excitations also in superconducting samples of $YBa_2Cu_3O_{7-y}$," Fleury told us. Because the La_2CuO_{4-y} samples used in neutron scattering studies were not superconducting, the Bell Labs work presents direct evidence for a correlation between superconductivity and the magnetic fluctuations in the high-T_c materials. Meanwhile, magnetic studies of $YBa_2Cu_3O_{7-y}$ have taken another step forward with the confirmation by both muon-spin rotation and neutron scattering studies that it too undergoes a transition to an antiferromagnetic phase.[3] The Néal temperature is about 400 K when y is 0.85, and it is higher than 500 K when y is 1.



Intensity of neutrons scattered by a single-crystal sample of La_2CuO_{4-y} at 200 K oriented with its CuO_2 layers normal to the scattering plane, as a function of direction (h,0.59,0) of momentum transfer relative to the CuO_2 layers. When h is 1, that is, when neutrons are scattered along the tetragonal axis of the crystal, the integrated intensity (red) shows a peak but the elastic scattering (black) is quite insignificant. The peak appears flat-topped because of the orthorhombic distortion of the crystal structure. The intrinsic width of the peak gives a value greater than 200 Å for the length scale of instantaneous correlations between copper spins in the CuO_2 layers. (Adapted from reference 1.)

Heisenberg antiferromagnets

The magnetic correlations in both La_2CuO_{4-y} and K_2NiF_4 are predominantly two dimensional because the magnetic coupling between successive CuO_2 or NiF_2 layers is weaker by several orders of magnitude than the coupling between moments within these layers. The Heisenberg exchange Hamiltonian, which derives its name from the work by Werner Heisenberg, Paul A. M. Dirac and J. H. Van Vleck on the quantum mechanical consequences of exchange of identical particles, is a good model for the interaction between moments in the CuO_2 or NiF_2 layers. The model is defined by the energy function, or the Hamiltonian operator

$$H = -J\sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

for the interaction of spin operators $\mathbf{S}_i$ at sites i of a lattice with spin operators $\mathbf{S}_j$ at sites j that are nearest neighbors of i. For a pair of spins, the energy is lower for parallel spins if J is positive (ferromagnetic), and it is lower for antiparallel spins if J is negative (antiferromagnetic). Determining the ground state of Heisenberg antiferromagnets for various values of the spin quantum number and for lattices of different dimensionalities has been an important problem in quantum statistical mechanics.

Hans Bethe (now at Cornell University), in a classic 1931 paper that Anderson regards as "one of the most beautiful in mathematical physics," obtained the exact ground state of the spin-$\frac{1}{2}$ antiferromagnetic Heisenberg model in one dimension.[4] Bethe's *Ansatz* for the ground state of the one-dimensional Heisenberg model has given rise to a whole new area of theoretical and mathematical research into one-dimensional many-particle systems. But questions about the physical content of his wavefunction and about those of its features that are relevant to the Heisenberg model in higher dimensions are only now being seriously addressed. There are two reasons for this renewed interest in Bethe's wavefunction: First, the unusual magnetic correlations in La_2CuO_{4-y} bear some resemblance to the behavior expected in a one-dimensional spin-$\frac{1}{2}$ Heisenberg model;[1] second, there is no consensus yet on the ground state of the two-dimensional antiferromagnetic Heisenberg model for different values of the spin.

Resonating valence bonds

In a 1973 paper Anderson argued that the Néel state, which has long-range antiferromagnetic order, may not be the ground state of the spin-$\frac{1}{2}$ antiferromagnetic model on a two-dimensional triangular lattice. Instead, Anderson proposed a singlet ground state that is like Bethe's ground state for the one-dimensional model. In the ground state Anderson proposed, every spin is paired in a singlet configuration with another one, so that the total spin of the whole lattice is zero. The pairs are not fixed: A spin has a finite probability of pairing with any one of its nearest neighbors or, more generally, with any other spin in the lattice. The ground state wavefunction, therefore, is a linear combination of the quantum mechanical states for different configurations of singlet spin pairs on the lattice. If the spin pairs are represented by bonds connecting the corresponding lattice sites, then the configurations may be transformed into one another by moving the bonds. Or, as Anderson said using a term from organic chemistry, the bonds defined by spin pairs "resonate" between different configurations. (See the figure on page 22.) The fate of the spin degrees of freedom in some versions of the resonating-valence-bond state is similar to that of position and velocity coordinates in a liquid—both are characterized by short-range, or cluster, correlations, which are stable up to a characteristic time scale that does not diverge in the thermodynamic limit. The spin degrees of freedom in the Néel state, by contrast, behave similarly to the position coordinates of atoms in a crystal.

"It is our hypothesis that pure La_2CuO_4 is in an RVB state," Anderson wrote in his first paper on the theory of the new high-temperature superconductors.[3] The few measurements of the magnetic susceptibility of La_2CuO_4 then available, he said, supported his proposal. Detailed theoretical studies of the stability of the RVB state for a two-dimensional square lattice did not exist at the time. Anderson argued, however, that the two-dimensional square lattice "will undoubtedly exhibit an RVB state" if, for example, "next-nearest-neighbor antiferromagnetic interactions frustrate the Néel state." Morrel Cohen (Exxon Research and Engineering Company) and David Douglass (University of Rochester) supported Anderson's argument for the conditions that might favor an RVB-type ground state for the two-dimensional CuO_2 layers.[6]

The excitations about the RVB state, first explicitly discussed by Steve A. Kivelson (State University of New York at Stony Brook) and Daniel S. Rokhsar and James P. Sethna (Cornell University), are different from spin waves, the low-energy magnetic excitations in ordinary metals and semiconductors, which arise from the slow, spatially periodic deviation of the direction of spins from that in the perfect Néel state.

Excitations in conventional solids have spin $\frac{1}{2}$ and obey Fermi statistics if they have an odd integer value of electrical charge, and they have spin 1 or 0 and obey Bose statistics if they have an even integer charge value. For excitations about the RVB, however, this charge–spin relationship does not hold; only that between spin and statistics does.[7] Thus there are charged bosons and neutral fermions. "Imagine a lattice with a half-filled electron band—there are as many electrons as lattice sites but each site can accommodate two electrons of opposite spin. The electrons in the RVB state are localized on lattice sites; they may flip their spins so as to be always bound in singlet pairs with other electrons, but they are not free to hop to different sites because a state in which two electrons occupy the same site has higher energy," Sethna said to explain to us how the charge–spin relationship gets inverted in the RVB state. "Now imagine adding just one more electron to this lattice," Sethna continued. "Every site this electron hops to has two electrons with total spin 0, such that when the electron moves from one end of the lattice to the other, a unit of charge is transported; the motion in the lattice, however, is that of a spin-0 bosonic object." A similar situation applies when an electron is removed from the half-filled band: The holes in the RVB state are bosons. Anderson and his colleagues at Princeton call these bosons holons. On the other hand, an excitation in which electrons on adjacent sites successively flip their spins will transport no charge although it will transport half a unit of spin. The Princeton group calls this excitation a spinon.

Spinons and holons are not the only examples in solid-state physics of excitations that do not obey the usual charge–spin relationship. In fact, the analysis by Kivelson, Rokhsar and Sethna was motivated by domain walls in polyacetylene, a one-dimensional conductor, which carry either spin or charge, as Wu-Pei Su (University of Houston), Robert Schrieffer and Alan J. Heeger (University of California, Santa Barbara) discussed in 1980. Spinons, holons and the domain walls in polyacetylene are also collectively called solitons. The term "soliton" was initially coined for the solitary-wave, or nondispersive, solutions to nonlinear wave equations. Spinons and holons are not solitons in this original sense. They are topological excitations—they cannot be defined locally at any one lattice site, but their dynamics and statistics depend on the arrangement of singlet pairs on the lattice. And like the solitary-wave solutions, they are extended, particle-like objects with conservation laws.

Until January 1987, Anderson's 1973 proposal of the RVB state was little known outside the group of experts working on two-dimensional antiferromagnets. Now, however, experimenters and theorists are working together to gain a proper understanding of this quantum state. Anderson told us, for example, that a singlet spin pair with partners very far apart may be broken with arbitrarily small cost in energy. This means that spinons' energy may be arbitrarily small, or that the spinon spectrum is "gapless." This feature of the spinon spectrum allows Anderson to explain a firmly established experimental fact, namely, that the high-temperature superconductors exhibit a linear temperature variation of specific heat at low temperatures. Spinons, although uncharged, are fermions. And Lev Davidovich Landau showed in 1957, in his celebrated theory of the Fermi liquid, that the specific heat of a collection of Fermi-type gapless excitations varies linearly with temperature at low temperatures.

Spinons or spin waves?

The two-dimensional correlations the Brookhaven–MIT–NTT team has observed in La_2CuO_{4-y} above its Néel temperature, Shirane and Birgeneau say, are qualitatively consistent with the two-dimensional quantum-spin-liquid behavior such as that postulated by the RVB theory for copper spins in La_2CuO_{4-y}. Shirane would like theorists to make more predictions that could be tested quantitatively in neutron scattering experiments. Anderson has suggested that, because the spinon spectrum is gapless, the spectrum of spin fluctuations has an inverse square-root singularity that should give rise to peaks in neutron scattering.[5] He told us, however, that the peaks would be very close together and the resolution might have to be increased by at least an order of magnitude to separate them. An alternative, he said, would be to use "hot," or higher-energy, neutrons, for they might allow probing further up the dispersion curve.

Sudip Chakravarty (SUNY, Stony Brook) and Bertrand Halperin and David Nelson (Harvard University) meanwhile have proposed[8] an alternative, but somewhat more conventional, explanation for the unusual antiferromagnetic correlations in La_2CuO_{4-y}. The Néel state is unstable at finite temperatures in two dimensions, even if quantum fluctuations are ignored. But to determine whether it is the ground state, Chakravarty, Halperin and Nelson used a renormalization group procedure for both thermal and quantum fluctuations to study the spin-wave stiffness, which measures the ease with which spins may be twisted from their orientation in the Néel state, and the effective antiferromagnetic interaction. Their conclusion: Experimentally measured values of the correlation length and of the spin-wave velocity imply that the Néel state is the ground state for the antiferromagnetic Heisenberg model on a two-dimensional square lattice. The antiferromagnetic correlations at finite temperature, in their analysis, are formally similar to those in a system approaching the Néel state at zero temperature, but they are modified, quantitatively, by quantum fluctuations. "For example, quantum fluctuations reduce the spin-stiffness constant to about 40% of its classical value," Halperin said. "Without such a reduction, the measured value of the spin-wave velocity would have implied a correlation length at least 400 lattice constants long at 300 K, which is an order of magnitude longer than is actually observed." Chakravarty, Halperin and Nelson believe that RVB-type ground states—they call them "quantum disordered" states—are possible for the two-dimensional Heisenberg antiferromagnet under some conditions, such as the presene of next-nearest-neighbor interactions. Halperin also told us that recent Monte Carlo simulations by Peter Young and Joseph Reger (University of California, Santa Cruz) and detailed quantitative analysis by David Huse (AT&T Bell Laboratories) suggest strongly that the ground state of the standard, nearest-neighbor spin-½ Heisenberg antiferromagnet has antiferromagnetic order.

Fluctuations about the Néel state should scatter neutrons quasi-elastically, Anderson told us. Conclusive evidence of such scattering should help answer, therefore, whether a single CuO_2 layer of La_2CuO_{4-y} is in the RVB state or the Néel state at zero temperature. This requires both more detailed analysis of the present data and more refined experiments. The situation could be complicated, Anderson added, if spinons "spawn their own spin waves."

Neutron scattering

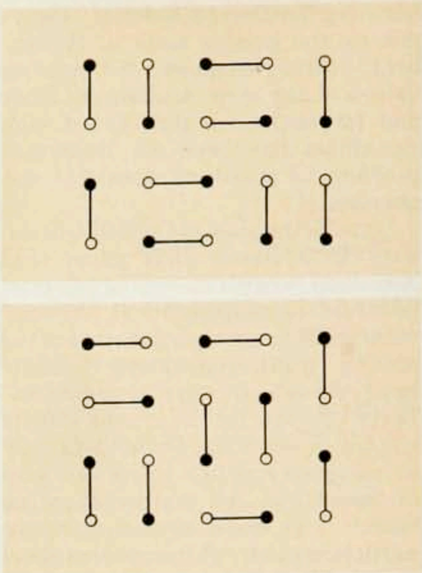
The cross section for the scattering of neutrons by spins in a solid is directly proportional to the **k** and ω components of the Fourier transform—in space as well as time variables—of the spin–spin correlation function if the scattering changes the neutrons' momentum by **k** and their energy by ω. The Bragg, or elastic, scattering ($\omega = 0$) at definite values of the momentum transfer that reveal the spin arrangement in the lattice is the signature for long-range magnetic order. On the other hand, integrating the cross section over ω for a given value of the momentum transfer measures the same Fourier component of the instantaneous, or equal-time, correlation function.

The Brookhaven–MIT–NTT team succeeded in integrating the cross section over energy by a clever choice of the scattering geometry. The experiment used a single crystal of La_2CuO_{4-y}, about 0.5 cm^3 in volume, that was mounted so that the CuO_2 layers were perpendicular to the scattering plane. The momentum transferred along the CuO_2 layers by neutrons scattered normal to the layers was independent of the magnitude of the final momentum. Collecting all neutrons with final momenta normal to the CuO_2 layers therefore effectively integrated the cross section over a wide range of energy transfers. (See the figue on page 20.) Birgeneau, Shirane and J. Skalyo Jr had used a similar geometry to study instantaneous correlations in K_2NiF_4 in 1971.

The single crystal used in this study was grown at NTT using a copper oxide flux technique. "We were very fortunate that our collaborators at NTT produced a large single crystal suitable for neutron scattering studies," Shirane said. "Single crystals as large as the one we used were not available anywhere else at the time we started our experiment [in the summer of 1987]."

Light scattering

The technique that Fleury and Lyons used at Bell Labs to study La_2CuO_{4-y} and $YBa_2Cu_3O_{7-x}$ is similar to the one Fleury had earlier employed in studies of magnetic fluctuations in K_2NiF_4. The Bell Labs group finds, among other things, a broad peak near 3000 cm^{-1} in the spectrum of light scattered inelastically by single crystals of La_2CuO_{4-y}. (The wavelength of incident laser light was between 4579 Å and 5145 Å.) The peak is significantly diminished or goes away altogether when the elec-



Resonating-valence-bond state. The figure shows two states that differ in the arrangement of singlet spin pairs. The RVB state is a superposition of all such states.

tric vectors of either the incident or the scattered light lie normal to the CuO_2 layers. These polarization selection rules are identical to those observed in K_2NiF_4 and predicted for spin-pair excitations, and they identify the peak in La_2CuO_{4-y} as also being due to scattering by magnon pairs. (Magnons are the quanta of spin waves.) In two-magnon scattering both the incident and the scattered electric vectors must have a nonzero component along the vector distance between the two spins that are flipped in the process. Fitting the position of the peak to the dispersion relation for antiferromagnetic spin waves yields a value of 0.74 eV–Å for the slope of the dispersion curve, which determines the spin-wave velocity, and of about 1000 cm^{-1} for the antiferromagnetic exchange interaction. The value for the slope is consistent with, but significantly greater than, the lower limit (0.4 eV–Å) obtained in neutron scattering studies. Fleury cautions, however, that the peaks in La_2CuO_{4-y} are considerably broader than what the two-magnon theory predicts. Fleury's data, Anderson told us, are consistent with the RVB theory, where they represent four-spinon rather than two-magnon scattering.

The peak in the light scattering persists in all samples of La_2CuO_{4-y} that the Bell Labs group studied—even in ones that did not show any transition to the antiferromagnetic phase between 4 K and 300 K. The position and the intensity of the peak show only a weak dependence on temperature. This feature, Fleury said, provides further support for the interpretation that the peak arises from highly energetic two-dimensional magnetic fluctuations.

Lyons and Fleury have also observed spin-pair excitations in inelastic scattering of light from single crystals of $YBa_2Cu_3O_{7-y}$. The peak in $YBa_2Cu_3O_{7-y}$ obeys selection rules identical to those observed in La_2CuO_{4-y} and K_2NiF_4, but its position moves, in wavenumbers, from 2600 cm^{-1} to less than 2000 cm^{-1} as y increases from 1 to 0 and the T_c for superconductivity increases to 90 K. This peak is even broader than that in La_2CuO_{4-y}, but it provides the only evidence to date for the existence of highly energetic spin excitations in superconducting samples.

Anisotropies?

Each spin in K_2NiF_4 prefers to align itself along the tetragonal axis, quite independently of the exchange interaction with its nearest neighbors. This so-called single-site anisotropy, although it is small (0.073 meV) compared with the exchange interaction (9.68 meV), is the reason why moments in the NiF_2 layers want to order themselves at 97 K—that is, why the layers show critical fluctuations near this temperature—contrary to the behavior expected for two-dimensional Heisenberg systems. By contrast, Birgeneau told us, the single-site anisotropy in La_2CuO_{4-y} is smaller than the exchange interaction by about five orders of magnitude. Thus the CuO_2 layers of La_2CuO_{4-y} provide a good realization of the spin-½ antiferromagnetic Heisenberg model.

While the ground state of the Heisenberg model and the nature and source of the two-dimensional correlations in La_2CuO_{4-y} remain unsettled questions, there already exist a variety of mechanisms that derive superconductivity in these materials from electrons' interaction with some sort of magnetic fluctuation. For example, Schrieffer told us that the results from neutron scattering studies were very "satisfying," for he had proposed—in collaboration with Xiao-Gang Wen and Shou-Cheng Zhang, and just before the Brookhaven–MIT–NTT team announced its results—a mechanism for superconductivity in which two holes attract each other when they are separated by a distance shorter than the magnetic correlation length.[9] Schrieffer and his colleagues view the long-range antiferromagnetic order in La_2CuO_{4-y} as a special case of a more general state, called the spin-density-wave state, in which the spatial arrangement of spins has the form of a sinusoidal wave. The electrons are "itinerant," or mobile, in this state. Doping La_2CuO_{4-y} with barium or strontium creates holes in the electron band. These holes distort the spin-density wave locally. The spatial extent of this distortion defines a region, called a bag. "Two such 'spin bags' attract because it is energetically favorable for two holes to be in the same bag," Schrieffer told us. "And this is what leads to superconductivity." The mechanism is conceptually similar to the one proposed in the "bag models of hadrons" in the 1970s to obtain hadrons from quarks.

Many different mechanisms for superconductivity have been proposed in the context of the RVB theory, Anderson told us. Recent Monte Carlo simulations suggest that it may not be energetically favorable for electrons in a single CuO_2 layer to pair if the correlations between them, which hinder double occupancy of lattice sites, are as strong as postulated in the RVB theory.[10] J. Wheatley and T. Hsu (Princeton University) and Anderson have developed a theory in which pairing between electrons arises from their tunneling between CuO_2 layers.[11] In this theory, the spinons and holons of the RVB state continue to live in individual CuO_2 layers, but they combine to form electrons, which may tunnel to adjacent layers.

According to Shirane, we now understand why we know of only two families of high-temperature superconductors—the 40-K superconductors obtained by doping La_2CuO_{4-y}, and the 90-K superconductors $RBa_2Cu_3O_{7-y}$, where R is a rare earth element. The reason, he says, is that these are the only examples we know of the two-dimensional, spin-½ Heisenberg antiferromagnet. What about K_2CuF_4? we asked. "That unfortunately is a ferromagnet," Shirane said.

—ANIL KHURANA

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