tracers has been found: a few hundred years ago there was a large pulse of ice in the southern Ross Embayment, but the flow after that pulse reverted to what it was beforehand (*10*). In fact, the proportion of ice flowing into the Ross Ice Shelf from East and West Antarctica, respectively, has remained approximately constant over the full 1500 years (*11*). This implies that the total outflow in the Ross Embayment has remained relatively unchanged despite the large internal perturbations, which points to a stable, not an unstable, system. Furthermore, glaciological studies of several types have all indicated that there has been no drastic change in the last 30,000 years in the height or flow of the ice sheet within the interior Ross Embayment (*12*). Study of the third major drainage from the WAIS, into the Ronne Ice Shelf, also suggests that there is no gross discordance between the present velocity vectors and flow tracers in the ice shelf, although the evidence is limited (*13*).

In light of the evidence for recent stability, it is difficult to see how climate warming (whether anthropogenic or natural) could trigger a collapse of the WAIS in the next century or two. Ice sheets take thousands of years to respond to changes in surface temperature, because it takes that long for the temperature changes to penetrate close to the bed and only at the bed could increasing temperatures affect the flow rates in any major way. Oceanic warming could cause thinning of the ice shelves, but recent studies with global circulation models have suggested that oceanic warming in the far southern ocean from, say, an enhanced greenhouse effect would be delayed by centuries compared to the rest of the world because of the large-scale sinking of surface waters around Antarctica (*14*). Furthermore, for reasons already cited, it is questionable whether ice-shelf thinning would have any drastic effect on the inland ice. Thus, I believe that a rapid rise in sea level in the next century or two from a West Antarctic cause could only occur if a natural (not induced) collapse of the WAIS is imminent, the chances of which, based on the concept of a randomly timed collapse on the average of once every 100,000 years, are on the order of 0.1%.

References

1. R. A. Warrick *et al.*, in *Second Assessment Report of the Intergovernmental Panel on Climate Change: Contribution of Working Group I*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1996).
2. J. Weertman, *J. Glaciol.* **13**, 3 (1974).
3. R. H. Thomas and C. R. Bentley, *Quat. Res.* **10**, 150 (1978); R. H. Thomas, T. J. O. Sanderson, K. E. Rose, *Nature* **277**, 355 (1979).
4. R. C. A. Hindmarsh, *Ann. Glaciol.* **23**, 24 (1996); in *Ice in the Climate System*, W. R. Pelier, Ed. (NATO ASI Series 1, Springer-Verlag, Berlin, 1993), vol. 12, pp. 67–99; private communication.
5. D. R. MacAyeal, *Nature* **359**, 29 (1992).
6. W. S. Broecker, *ibid.* **372**, 421 (1994).
7. D. R. MacAyeal, *Paleoceanography* **8**, 775 (1994).
8. S. Shabtaie and C. R. Bentley, *J. Geophys. Res.* **92**, 1311 (1987); C. R. Bentley and M. B. Giovinetto, in *International Conference on the Role of the Polar Regions in Global Change*, G. Weller, C. L. Wilson, B. A. B. Severin, Eds. (Geophysical Institute, University of Alaska, Fairbanks, 1991), pp. 481–488; B. K. Lucchitta, C. E. Rosanova, K. F. Mullins, *Ann. Glaciol.* **21**, 277 (1995).
9. R. Retzlaff and C. R. Bentley, *J. Glaciol.* **39**, 553 (1993); C. R. Bentley, P. D. Burkholder, T. S. Clarke, C. Liu, N. Lord, *Antarct. J. U.S.*, in press; S. Shabtaie, private communication.
10. G. Casassa, K. C. Jezek, J. Turner, I. M. Whillans, *Ann. Glaciol.* **15**, 132 (1991).
11. C. R. Bentley, in *Sea Level, Ice, and Climatic Change* (IAHS Publ. 131, IAHS Press, Wallingford, UK, 1981), p. 247.
12. I. M. Whillans, *Nature* **264**, 152 (1976); in *The Climatic Record in Polar Ice Sheets*, G. de Q. Robin, Ed. (Cambridge Univ. Press, Cambridge, 1983), pp. 70–77; D. Raynaud and I. M. Whillans, *Ann. Glaciol.* **3**, 269 (1982).
13. C. S. M. Doake, private communication.
14. S. Manabe, R. J. Stouffer, M. J. Spelman, K. Bryan, *J. Clim.* **4**, 785 (1991).

CONDENSED MATTER THEORY

Superconductivity and Antiferromagnetism in High-T_c Cuprates

Naoto Nagaosa

Ten years have passed since the discovery of the high–transition temperature (T_c) superconductors. Although there has been no agreement on a complete theory, a consensus has formed that the strong electron repulsion and the quasi–two-dimensional layered nature of these materials are responsible for their anomalous physical properties and high T_c. On page 1089 of this issue, Zhang describes a theory that relates one important property of these materials, their superconductivity, with another, the phenomenon of antiferromagnetism.

The repulsive electron interaction in the cuprates tends to increase the spin moments because it reduces the probability of two electrons with opposite spins occupying the same orbital and hence breaks the cancellation of the spin moments. An antiferromagnetic (AF) exchange interaction occurs between these induced spin moments because an electron can hop to the neighboring site without violating Pauli's exclusion principle if the spin there is antiparallel. This virtual process lowers the energy. In high-T_c oxides, the exchange energy J is estimated experimentally to be around 0.15 eV. This large value of J is considered to be responsible for the high T_c, and the final theory of high-T_c superconductivity should include an appropriate treatment of this AF interaction. There are two consequences of this interaction: (i) it induces an AF magnetic long-range ordering (Néel state), and (ii) it causes formation of the singlet pair. Zhang proposes an ambitious theory based on SO(5) symmetry that unifies these two aspects (*1*).

A schematic phase diagram of carrier concentration x versus temperature for high-T_c superconductors is shown in the figure. At $x = 0$, there is one electron per copper orbital (half-filled), and band theory predicts the metallic state. However, the strong Coulomb interaction blocks the band motion, and each orbital is occupied by a single localized electron; that is, the system is a Mott insulator. In this Mott insulator, the spins are aligned antiferromagnetically because of the AF interaction mentioned above. This ordering of the spins is destroyed by the doping, and the region of so-called "pseudo gap state" appears, where the pseudo gap is observed well above T_c in nuclear magnetic resonance, neutron scattering, specific heat, photoemission, and infrared optical spectra perpendicular to the plane (*2*).

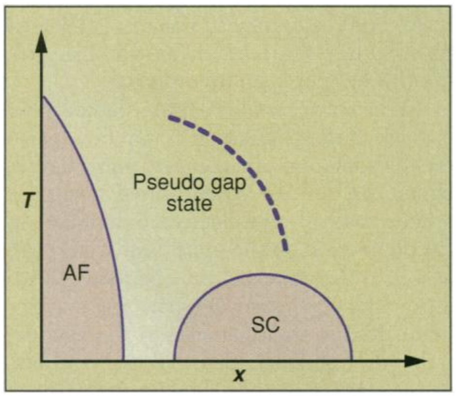
Here some remarks are in order on the symmetry of the pairing. Let $\psi(\mathbf{r})$ be the spatial wave function for the relative motion of the Cooper pair. The total wave function is the product of the spatial and spin parts. Because of the antisymmetry to the exchange of the two electrons, spin-singlet (-triplet) pairing is accompanied by the even (odd) function for $\psi(\mathbf{r})$. When decomposed into the partial waves, $l = 0$ (s wave), $l = 2$ (d wave), and higher even terms correspond to the spin-singlet pairing, whereas $l = 1$ (p wave), $l = 3$, and higher odd terms correspond to the spin-triplet pairing. In the usual BCS (Bardeen-Cooper-Schrieffer) superconductors, the s-wave pairing is a result of the weak attractive force, mediated by means of the electron-phonon interaction. With

The author is in the Department of Applied Physics, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan. E-mail: nagaosa@appi.t.u-tokyo.ac.jp

the strong repulsive interaction, as in the case of high-T_c cuprates, the s-wave pairing is not possible. However, by forming the anisotropic pairing ($l \geq 1$), one can avoid this strong on-site repulsive interaction, because $\psi(\mathbf{r} = 0) = 0$, and can even gain the effective attractive force on the neighboring sites. Recently the pseudo gap has been confirmed in angle-resolved photoemission spectra, showing that the symmetry of the pseudo gap is $d_{x^2-y^2}$ (2). As the temperature is lowered, superconductivity appears whose symmetry is again $d_{x^2-y^2}$. This has been shown convincingly by interference experiments, including those with Josephson junctions. As a result, the intimate relation between the pseudo gap and superconductivity is the issue of current interest.

There are two streams of thinking on this problem. One is to look at the (staggered) spin moment $\mathbf{n}(\mathbf{r})$ and study its fluctuation, which is coupled with the electrons (3). The superconductivity is mediated by the exchange of spin fluctuations, which leads to the $d_{x^2-y^2}$ pairing. A related approach is the so-called spin-bag theory, which assumes the coexistence of the (short-range) AF order and the superconductivity (4). Another stream originates from the resonating valence bond (RVB) picture proposed by Anderson (5), where the emphasis is being put on the spin-singlet pairs, the configurations of which are resonating quantum mechanically to form a quantum spin liquid. Although it is established that the ground state of the undoped material is the Néel state, let us assume that the spin system is in the RVB state. Then each site is occupied by one electron, but the spin is quenched by the singlet formation. This is the vacuum of the RVB theory. Now we take an electron from this vacuum. Then a vacant site appears with the positive charge $+e$ but no spin compared with the vacuum. There also appears a site where the spin loses its partner and cannot form a singlet; this site has spin 1/2 but no charge compared with the vacuum. These two particles are called holons and spinons, respectively, and if they move rather independently, the charge and spin degrees of freedom behave quite differently from those of the usual metals. This phenomenon is called the charge-spin separation. In this picture, the singlet pairs are already formed well above T_c (broken line in the figure), and the onset of the superconductivity is governed by the coherence of the holons (6).

The most essential theoretical problems posed by the high-T_c superconductors are how to unify these two pictures—namely, the magnetic fluctuation and singlet formation—and how to describe the crossovers from the Néel to the superconducting states. To accomplish this goal, Zhang (1) introduced the five-component vector n_α ($\alpha = 1,2, \ldots ,5$), with $n_1 = \Delta^\dagger + \Delta$ and $n_5 = -i(\Delta^\dagger - \Delta)$ being the real and imaginary parts of the d-wave pairing order parameter and $\mathbf{n} = (n_2, n_3, n_4)$ the staggered magnetic moment. In this representation, the rotation in the (n_1, n_5) plane corresponds to the phase (gauge) transformation, and the rotation in spin space is that of $\mathbf{n}$. Up to this point nothing is new, but Zhang has further shown that the symmetry can be enlarged into $SO(5)$. $SO(5)$ is the symmetry group consisting of 5×5 orthogonal matrices with the determinant being unity. This $SO(5)$ is the rotational symmetry in the five-dimensional space of n_α. Then one can consider the generalized "magnet" with the five-dimensional "superspin." The broken line in the figure, that is, the onset of the pseudo gap, is interpreted as the



Schematic phase diagram of a high-T_c superconductor. Solid lines are transition temperatures versus carrier concentration x. At low carrier concentrations, electron repulsion causes an exchange interaction leading to an antiferromagnetic ordering (AF). At higher doping, a superconducting region is created (SC) with the pseudo gap state above it. Zhang's theory (1) unifies the AF and SC states by means of an $SO(5)$ symmetry principle.

gradual growth of the amplitude of this superspin, and the superconductivity with d-wave pairing and the Néel state correspond to some direction of this "superspin." Then these two states are connected by some rotation, and the hole doping x controls the anisotropy in this superspin space to create the phase diagram, including both Néel state and d-wave superconductivity as in the figure.

In quantum mechanics, the operators generating the symmetry transformations—for example, time evolution, translations, and rotations—play important roles. These operators are called generators, and it is natural to ask what are the generators of these rotations in the superspin space. The rotations that mix (n_1, n_5)-plane and $\mathbf{n}$-space are, in particular, nontrivial. Zhang and Delmer (7) had already found those generators in the theory of the resonant peak observed in the neutron scattering experiments (8). This peak is sharp in both energy (ω = 41 meV) and momentum [near (π, π)] and grows only below T_c (8). They found that the generators enter into the spin-spin correlation function when the superconducting order parameter is nonzero, which they interpreted as the 41-meV peak.

Although Zhang's report includes many interesting ideas and opens up a new direction, there still remain open questions to be answered:

1) When one considers the quantum numbers of the excitations, there are essential differences between Anderson's RVB theory and Zhang's theory. In Zhang's theory there is no room for the charge-spin separation in the sense used by Anderson. In other word, the holons and spinons are confined to form spin-singlet or spin-triplet objects of charge $2e$ or 0, respectively, at low energy. This issue should be studied further in comparison with the experiments, especially the transport properties.

2) There are other systems whose phase diagrams show the proximity of superconductivity and antiferromagnetism. These include heavy fermion systems (such as the U and Ce compounds) and organic conductors {such as the TMTSF (tetramethyltetraselenafulvalene) and BEDT-TTF [bis-(ethylenedithio)–tetrathiafulvalene] compounds}. Then it is important to study the similarities and dissimilarities of high-T_c oxides with these systems, which will clarify the role of dimensionality and the strength of the correlation.

3) Recently, several copper oxides with two-leg ladder structure have been studied extensively (9). These systems show the gap in the triplet excitations in the undoped case, and some of them show superconductivity with doping under pressure. This superconductivity is expected to be closely connected with that in the two-dimensional copper oxides, and hence, its study should shed further light on the mechanism of high-T_c superconductivity.

References

1. S. C. Zhang, *Science* **275**, 1089 (1997).
2. N. P. Ong, *Science* **273**, 321 (1996), and references therein.
3. N. E. Bickers, D. J. Scalapino, S. R. White, *Phys. Rev. Lett.* **62**, 961 (1989); T. Moriya and K. Ueda, *J. Phys. Soc. Jpn.* **63**, 1871 (1994); D. Pines, *J. Phys. Chem. Solids* **54**, 1447 (1993).
4. J. R. Schrieffer, X. G. Wen, S. C. Zhang, *Phys. Rev. B* **39**, 11663 (1989).
5. P. W. Anderson, *Science* **235**, 1196 (1987).
6. Y. Suzumura, Y. Hasegawa, H. Fukuyama, *J. Phys. Soc. Jpn.* **57**, 2768 (1988); N. Nagaosa and P. A. Lee, *Phys. Rev. Lett.* **64**, 2450 (1990).
7. E. Delmer and S. C. Zhang, *Phys. Rev. Lett.* **75**, 4126 (1995).
8. H. Mook *et al.*, *ibid.* **70**, 3490 (1993); H. F. Hong, *ibid.* **75**, 316 (1995).
9. S. Maekawa, *Science* **273**, 1515 (1996), and references therein.