Yoon results, these animals still developed diabetes. In fact, it was found that the mice were not tolerant to GAD (*10*, *11*). One study showed that despite the presence of the entire GAD protein in hematopoietic cells, autoantigenic GAD peptides were not presented on the surface of these cells (*11*). Thus, the GAD in pancreatic islet cells may be proteolytically cleaved to generate a completely different set of peptides not found in other cells. Given the results presented in the Yoon report, it may be worthwhile to express the relevant GAD epitopes before the immune system develops, thereby inducing effective tolerance by intrathymic deletion of immature T cells (*12*, *13*). This would require inserting a transgene into the germ line, clearly taboo in humans. To treat human diabetes in this way one would have to effectively induce tolerance in mature T cell populations in young individuals with a genetic predisposition to the disease. This is not easy: Tolerance induction in mature T cells is often preceded by a brief effector phase before the T cells become anergic or are deleted, which would pose a risk of accelerating the disease (*14*, *15*).

The finding by Yoon *et al.* that GAD is the initiating antigen of autoimmune diabetes is a major step toward formulating new therapies to treat this disease. The invaluable NOD mouse will enable the benefits of these new therapeutic strategies to be firmly established before their application in humans.

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PERSPECTIVES: CONDENSED MATTER PHYSICS

Is This Why T_c Is So Low?

A. V. Balatsky and Z.-X. Shen

Early in the effort to understand high–transition temperature (T_c) superconductors, Lee and Read asked a provocative question: Why is the T_c of cuprate superconductors so low (*1*)? The question stems from the fact that, knowing the natural energy scales in the high-T_c superconductors (such as the electron kinetic and potential energy), one would expect a much higher transition temperature than is observed experimentally. It is the pairing interactions between carriers that ultimately lead to the superconducting state. This superconducting state is stabilized by an energy gap. The stronger the pairing, the bigger the gap. Thus, more intense thermal fluctuations are required to destroy the superconducting state, and this means T_c is higher. For the cuprates as a class of high-T_c superconductors, the natural energy scales are much larger than the T_c, which is typically 50 to 100 K (or 0.005 to 0.01 eV). Moreover, researchers have discovered a "pseudogap," a gaplike feature in the particle energy spectrum that develops at temperatures substantially higher than T_c. This further establishes the notion that the pairing interaction, which is large, is not the limiting factor for T_c. The pseudogap has been identified so far for a certain range of carrier densities, the so-called underdoped regime. The large difference between natural energy scales in these materials and the T_c raises the question of whether there is a feature at lower energy that we have not yet identified that directly determines the transition temperature for these materials.

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There are a few clues on what this hidden T_c energy scale might be. One of the main properties of superconducting state is the formation of a phase coherent condensate capable of carrying electric current without dissipation. The fraction of particles participating in the condensate determines the superfluid density ρ_s. Thus, one clue comes from the so-called Uemura plot, which shows the direct proportionality between T_c and ρ_s (both experimentally measured quantities) in the underdoped regime, indicating that the energy scale is set by ρ_s (*2*).

Recently, new experimental findings have given more specific clues on the nature of the low-energy scale that determines the superconducting T_c. From inelastic neutron-scattering experiments, one finds a remarkably simple relation between T_c and the splitting of the incommensurate peaks or the peak (half) width δ near the antiferromagnetic wavevector (π,π) (*3*, *4*) [for explicitly observed incommensuration in YBCO123, see (*5*)]:

$$k_B T_c = \hbar v^* \delta \qquad (1)$$

where k_B is the Boltzmann constant and $\hbar$ is the Planck constant. This equation relates the energy scale $k_B T_c$ to the momentum scale δ, similar to the conventional $\omega = vk$ relation for excitation with energy ω and momentum k, propagating with some velocity v. On the basis of this very simple analogy, it was argued that the proportionality of T_c versus δ in fact implies very slow moving charge objects, whose phase coherence is responsible for the superconductivity. The characteristic velocity was found to be $\hbar v^* = 17$ meV-Å for underdoped LSCO and $\hbar v^* = 35$ meV-Å for YBCO123 (*4*), the two high-T_c compounds most studied by inelastic neutron scattering. Velocity v^* remains constant for the whole underdoped regime in both compounds. No theoretical assumptions are needed to extract v^* from Eq. 1. Any attempts to reconcile these values with the typical carrier velocity, called Fermi velocity (v_F), in high-T_c compounds fail. v^* values are about two orders of magnitude smaller than the Fermi velocity: $\hbar v_F \sim 1$ to 4 eV-Å from the band calculations or measured along $(0,0) \rightarrow (\pi,\pi)$ momentum direction (*6*, *7*). Simple estimates for the effective mass renormalization would yield the heavy charged excitations in the system with typical mass m^* relative to electron mass m: $v_F/v^* = m^*/m \sim 50$ to 100. The heavy charge mass m^* or, more precisely, the low charge mobility might be expected in these materials as a consequence of proximity to insulating state with no charge mobility.

The fact that small velocity enters into linear relation between T_c and inverse length scale δ (Eq. 1) implies that it is precisely these slow moving (heavy mass) objects that are responsible for the formation of the superconducting state. In contrast to the conventional description of superconductivity with electrons carrying the current without dissipation, Eq. 1 suggests that carriers of electricity

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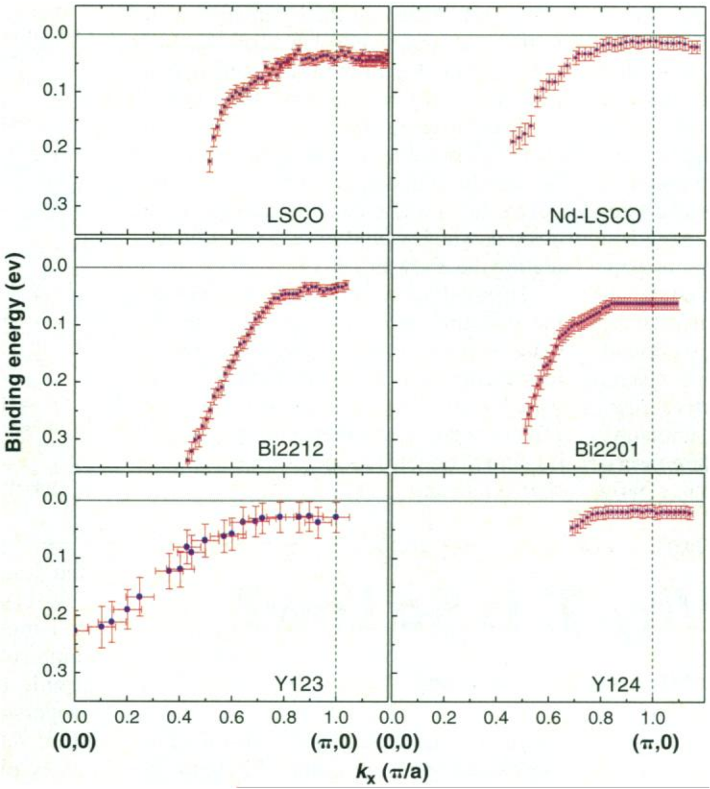

Look alikes. Energy versus momentum curves for six superconductors are shown [$La_{2-x}Sr_xCuO_4$ (LSCO), $La_{1.28}Nd_{0.6}Sr_{0.12}CuO_4$ (Nd-LSCO), $Bi_2Sr_2CaCu_2O_8$ (Bi2212), $Bi_2Sr_2CuO_4$ (Bi2201), $YBa_2Cu_3O_7$ (Y123) and $YBa_2Cu_4O_8$ (Y124)]. For $k_x \geq 0.8\pi/a$, the dispersion is substantial with $\hbar v$ ~ 1 eV-Å. For $k_x \geq 0.8\pi/a$, the dispersion is minimal with $\hbar v \geq 90$ meV-Å. Except for the Nd-LSCO case, the dispersions were determined by their "peak" position. The variation of its distance from the Fermi level is related to the pseudogap whose magnitude is influenced by doping and even surface effect (Y123 and Y124). Despite these variations, the flat band behavior is universal in all samples. The error bars are still too large to study the variation of v among different families of cuprates.

are heavy charged objects, rather than simple electrons.

We suggest that this v^*/v_F smallness is responsible for the "small" T_c scale in high-T_c superconductors. Indeed, Eq. 1 can be viewed as a simple relation, determining T_c for a particular compound once δ, which is dependent on carrier concentration, is known. The small scale of coefficient v^* (compared with single particle velocity v_F) in Eq. 1 is saying that T_c cannot be as large as one would expect.

Here we would like to draw attention to the intriguing connection between the velocity scale $v^* << v_F$ and the flat band. The flat band near momentum (π,0) with anomalously small changes of electron energy as a function of momentum is universally observed in hole-doped (p-type) superconductors (*7*). The figure shows the flat band dispersion for all families of p-type cuprates, studied by angular-resolved photoemission spectra (ARPES) (*8*). One sees less than 15 meV dispersion in the range between (0.8π,0) and (π,0), yielding an upper bound for a velocity scale:

$$\hbar v = |\partial_{\mathbf{k}}\varepsilon| \sim 90 \text{ meV-Å} \qquad (2)$$

There are several reasons to believe that v and v^* are connected. The first is the velocity scale: Nowhere else in the Brillouin zone (that is, in momentum space) can one find a small-velocity scale of this magnitude. The second stems from the recent ARPES data on Nd-LSCO (*9*). Here the flat band is part of the one-dimensional electronic structure, in a compound where the incommensurate neutron peak is elastic, which has been attributed to the formation of stripes (*10*). Small dispersion around (π,0) reflects the underlying electronic structure near a band saddle point or the slow motion of charges among the stripes—a possible origin of the heavy-mass objects (*11*, *12*). The static stripes so far have been observed only in the LSCO system; however, the flat band, found in all cuprates, is likely of the same vintage. The third reason is the finding that the flat band persists in the underdoped regime in LSCO (*13*). This is consistent with the fact that v^* does not depend on doping in the underdoped regime. The possible connection between v and v^* is also consistent with Eq. 1 and the interpretation of the incommensurate neutron peaks as due to stripes (*10*). Given that the flat bands are a universal feature in p-type cuprates and Eq. 1 holds for both LSCO and YBCO123, we suggest that Eq. 1 will hold for Bi2212 also. It would be interesting to see whether neutron-scattering experiments can verify it for Bi2212. This high-T_c compound has two Cu-O layers in the unit cell and we expect it will have a similar velocity scale $\hbar v^*$ ~ 40 meV-Å as in the YBCO system. If this turns out to be the case, it will strengthen the case that the heavy-mass objects near (π,0) are responsible for the formation of the superconducting state at the "small" T_c scale. These heavy-mass objects are probably hidden from our view in traditional experiments such as specific heat because of the pseudogap or the superconducting gap, developed near (π,0). There are at least two distinct possibilities as to what the nature of these charge objects is. One is that they are bosons that undergo a phase coherence transition and form a condensate at T_c, and another is that they are fermions that form a superconducting state at T_c. The data, discussed here, at present do not allow us to make the identification. New experiments with better resolution, such as ARPES and transport measurements are required to make this distinction and identify these charged objects.

The immediate questions arising from this discussion include the following: What is the nature of slow moving objects? What is the mechanism for superconductivity that allows for a simple relation Eq. 1 between T_c and doping-dependent length scale δ? We believe that uncovering the nature of these slow moving charge objects is a crucial step for our understanding of high-T_c superconductivity.

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