Superconductors are materials that lose all electrical resistance below a specific temperature, known as the critical temperature ($T_c$). Large-scale applications, for example, in superconducting cables, require materials with high (ideally room temperature) $T_c$'s, but most superconductors have very low $T_c$'s, typically a few kelvin or less. The discovery of a layered copper oxide (cuprate) with a $T_c$ of 38 K (see panel A in the first figure) in 1986 [1] raised hopes that high temperature superconductivity might be within reach. By 1993, cuprate $T_c$'s of 133 K at ambient pressure had been achieved [2,3], but efforts to further increase cuprate $T_c$'s have not been fruitful. Two reports by Schön et al. [4,5] in the current issue of science—applying a similar technique to two very different materials—drastically alter the perception that planar cuprates are the only route to high temperature superconductivity.

Schön et al. use a field-effect device introduced in previous investigations to transform insulating compounds into metals [6]. On page 2430, they show that copper oxide materials with a ladder structure (panel B in the first figure) can be superconducting [4], even without the high pressure applied in previous studies of related compounds. Even more spectacularly, they report on page 2432 that the $T_c$ of a noncuprate molecular materials, $C_{60}$ (panel C in the first figure), known before to superconduct at 52 K upon hole doping [7], can be raised by hole doping with intercalated CHBr$_3$ to 117 K [5], not far from the cuprate record. Simple extrapolations suggest that the $T_c$ could be increased even further, effectively ending the dominance of cuprates in the high-$T_c$ arena.

The idea behind the studies is conceptually simple. Field-effect doping exploits the fact that under a strong, static electric field, charge (electrons or holes) will accumulate at the surface of the material, effectively modifying the electronic density in that region. This is necessary to stabilize superconductors away from nominally insulating compositions. The dielectric portion of the field-effect device must be able to sustain electric fields large enough to induce a sufficient number of holes per atom or molecule for the material under study to become superconducting. In addition, the interface with the studied material must be as perfect as possible. Doping through a field-effect device [4,5] avoids imperfections that cause the system to deviate locally from its average properties. Such imperfections are inevitably induced by chemical doping. Disorder has not been seriously considered by most cuprate high-$T_c$ theorists, but its important role is slowly emerging. Some phase diagrams of cuprates may have to be redrawn when doping is introduced through a field-effect device [8].
experimentally in 1996, when a $T_c$ of 13 K was reported [10]. However, the superconducting state was stabilized with a high pressure of about 3 GPa. Ambient pressure ladder superconductivity, although searched for extensively, was not observed until now.

The previous negative results suggested that high pressure may transform the ladders into anisotropic two-dimensional systems (similar to the planar cuprates) by reducing interatomic distances [11]. However, Schön et al. show that ladders can become superconducting without high pressure, simply by a different doping procedure than previously used. Cuprate superconductivity is thus not unique to two-dimensional structures but exists in ladders as well, with similar copper and oxygen building blocks but a qualitatively different atomic arrangement.

The ladder compounds are conceptually important because they provide the only known superconducting copper oxide without a square lattice. The hypothesis that the ladder compounds are anisotropic two-dimensional systems appears difficult to sustain in view of the discovery reported in [4]. Furthermore, the resistivity at optimal doping (when $T_c$ is the highest) is linear with temperature [4]. This behavior, observed also in non-superconducting ladders [11], was previously believed to be a unique signature of the exotic properties of high-$T_c$ planar cuprates.

Crystalline $C_{60}$ is normally an insulator, but in 1991, it was shown that electron-doped fullerenes are superconducting [12]. Recently, the $T_c$ in these compounds was raised to 52 K by field-effect hole doping, suggesting that $T_c$ could be raised further by increasing the intermolecular distance – a quantity that was found to be almost linearly related to $T_c$ [7].

The new results [5] confirm these expectations. It is widely believed that hole-doped $C_{60}$ follows the standard model of superconductivity in which phonons (vibrations of the lattice and molecules) provide the source of attraction between carriers for pair formation and concomitant zero resistance. In fullerenes, high-energy intramolecular phonons are available to mediate the pairing. As the distance between molecules increases, the overlap of electronic wavefunctions decreases. As a result, the electronic bands narrow and the electronic density of states at the Fermi level ($E_F$) increases. These effects, supplemented by a substantial electron-phonon coupling ($\lambda$), appear to determine to a large extent the high value of the $T_c$. Smaller $C_{36}$ fullerenes are expected to have a larger $\lambda$ than $C_{60}$ [13], suggesting another route to higher $T_c$’s.

These arguments are persuasive and likely correct, but possible electronic pairing mechanisms should also be considered. Electron-electron interactions are characterized by an energy scale much larger than that of phonons and are more likely to generate high-$T_c$ behavior. Intramolecular pairing of whatever origin – phononic or electronic – may produce the same local effective attraction, usually referred to as “$-U$”. Denoting by $t$ the amplitude for electron hopping between $C_{60}$ molecules, in simple models for superconductivity the reduction of $t$ at fixed $|U|$ leads to an increase of $T_c$ in weak coupling [14], as in the present experiments [5], where the hopping is regulated by intercalating small molecules [15]. On the other hand, if $T_c$’s of more than 100 K can be achieved in fullerenes with just phonons, then the relevance of phononic mechanisms for cuprates should be reconsidered. Has nature given us only one way to induce high temperature superconductivity, after all?

![FIG. 2. Head-to-head race, $T_c$ versus year of discovery for some superconducting materials. Orange, representative low-$T_c$ compounds, which held the $T_c$ record before cuprates and fullerenes were discovered. Light blue, representative planar cuprates. Magenta, representative fullerenes, with the highest $T_c$ to date reported in [4].](image-url)
Superconductivity in field-effect doped materials is effectively two-dimensional, sandwiched between the undoped bulk material and the dielectric oxide. Is this effective lower dimensionality crucial for the high $T_c$ obtained? Results for electron-doped fullerenes suggest otherwise — bulk- and field-effect-doped compounds have similar $T_c$’s [7] — but the question is worth investigating. Correlating $T_c$ with the electronic density of states at $E_F$ would also allow for a more intuitive understanding of the results. The mechanism of increasing the density of states by reducing the bandwidth through the expansion of the lattice seems simplistic but appears to work. In theoretical studies of superconducting cuprates, band narrowing was caused by the antiferromagnetic background in which the holes are immersed. In this context, optimal doping is naturally associated with a peak in the density of states [16].

Through increasing the $C_{60}$ lattice constant by 1% [5] or improvements of the field-effect device, it may be possible to induce a $T_c$ above 133 K, the ambient pressure record for cuprates (see the second figure). However, the work on ladders [4] shows that cuprates can now also be doped by the field-effect device. An exciting organic vs inorganic race toward room-temperature superconductivity may be about to begin. If so, then field-effect doping will likely play a fundamental role.

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