be to immunize against antigens, particularly viral antigens, whose protective epitopes require conformations or modification, such as glycosylation and assembly, that cannot be acquired in most procaryotes. There is a precedent in viral systems, however, that priming for immunological memory at the level of the T-helper cell, as by immunization with influenza virus internal antigens, is sufficient to allow induction of accelerated antibody responses to the surface antigens upon infection with virus[28-30]. Thus, even if viral antigens expressed in rBCG fail to induce virus-neutralizing antibodies, immunological memory may be generated such that an efficient secondary response would be obtained following natural infection by virus. This would be particularly important as BCG, which is unaffected by maternal antibodies, can be given earlier in life than most viral vaccines. The hope would be that T-cell memory can ensure protection against severe morbidity and death. We believe these results establish the molecular and immunological foundation for a novel live-vaccine vehicle that may prove useful in stimulating both humoral and cellular immune responses to a wide variety of viral, bacterial and protozoal antigens. □

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LETTERS TO NATURE

Giant tunnelling anisotropy in the high-T_c superconductor $Bi_2Sr_2CaCu_2O_8$

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TUNNELLING spectroscopy has been one of the most fruitful methods in the study of superconductors[1,2]. Excellent agreement has been obtained between theory and experiment, and even the fine details of the tunnelling spectra for conventional, low-transition-temperature (low-T_c) superconductors have been explained in terms of electron–phonon interactions. The low-T_c materials are generally isotropic enough for accurate measurements to be made on polycrystalline specimens; in contrast, it has been difficult to obtain reliable and reproducible tunnelling data for the highly anisotropic high-T_c materials[3]. We have overcome these difficulties by performing break-junction tunnelling measurements[4] on extremely thin single crystals, and show here that the tunnelling spectra of $Bi_2Sr_2CaCu_2O_8$ are indeed highly anisotropic. In the superconducting state, for electrons tunnelling parallel to the copper oxide planes, there are no electronic states at the Fermi level. In the normal state the tunnelling conductance is nearly independent of the d.c. bias voltage. Tunnelling perpendicular to the copper oxide planes was found to be qualitatively different from that parallel to the planes, and we suggest that electron scattering processes play an important role here.

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In its most ideal realization, an electron tunnelling measurement provides us with the electronic density of states (DOS)[1]. In particular, for a superconductor–insulator–superconductor junction, one can directly measure the energy gap 2Δ by observing a sudden increase of conductivity at bias voltages, V, exceeding $2\Delta/e$ (here e is the electron charge). The bias-voltage-dependent tunnelling conductance (the 'tunnelling spectrum') is related to the energy-dependent DOS by a simple integral[1]. At low temperatures the conductivity of the junction is close to zero for $V < 2\Delta/e$, indicating zero DOS. For most of the low-T_c superconductors the experiments are very well described by BCS theory[5]. The copper-oxide-based high-T_c superconductors, however, did not exhibit the expected zero conductance[5,7]. One is forced to assume either that BCS theory is not valid for these materials, or that the electron transport cannot be described as an ideal tunnelling process. Is it possible, for example, that the tunnelling is strongly influenced by inelastic electron scattering? Complex tunnelling conductance curves and 'zero-bias anomalies' have been seen in junctions with magnetic impurities[8-13]. The well known structural anisotropy of the copper-oxide-based high-T_c superconductors may also result in nontrivial effects. The tunnelling process is inherently anisotropic, because the particles with non-perpendicular incidence angle are less likely to travel through the potential barrier. What happens if the Fermi surface of the material is so anisotropic that there are no electron momenta perpendicular to the junction surface?

We attempted to answer these questions by performing tunnelling measurements on break junctions[4] fabricated at low temperature, in vacuum. By using ultra-thin single crystals of $Bi_2Sr_2CaCu_2O_8$, we were able to obtain reproducible superconductor-insulator-superconductor tunnelling spectra in high-T_c superconductors. We found that parallel and perpendicular to the CuO planes, the tunnelling and its temperature dependence are very different. For 'in plane' tunnelling, a gap structure is visible at low temperatures, with the tunnelling conductance vanishing at zero bias. At temperatures above T_c, the conductance is nearly independent of the voltage. For 'perpendicular' tunnelling, conductance is always nonzero, and its temperature dependence is well approximated by a smooth function, with no reference to T_c.

For the tunnelling measurements in the 'a–b plane', we first cleaved a strip ~1,000 Å thick and 100 μm wide from a single crystal of $Bi_2Sr_2CaCu_2O_8$ (ref. 14). We mounted the ultra-thin specimen on a crystal of $Bi_2Sr_2YCu_2O_8$ (a high-resistance semiconductor). Electrical contacts to gold wires were made by silver epoxy. After the heat treatment the contact resistance was ~1 Ω; the four-probe room-temperature resistance of the sample varied between 20 and 300 Ω depending on the sample thickness and contact distance. The $Bi_2Sr_2CaCu_2O_8/Bi_2Sr_2YCu_2O_8$ assembly was glued to an elastic strip of metal and fixed on the cold finger of a helium-flow cryostat. A precision-mounted screw pushed the back of the metal strip. When the temperature reached ~10 K, a 'break junction' was produced by bending the metal strip with the screw.

For 'c-axis' tunnelling, we first prepared electrical contacts on the opposite, cleaved, surfaces of a crystal. We glued the sample to the inside of a U-shaped elastic strip so that the electrical contacts faced the two arms of the U. We cooled the device in vacuum and observed typical c-axis conductance: resistivity increasing with decreasing temperature, turning to superconductivity at T_c. At low temperature, the crystal was cleaved by increasing the separation between the arms of the U with the screw mechanism. The break junction was formed between the freshly cleaved surfaces. We also prepared junctions in air at room temperature. The c-axis tunnelling curves did not depend on the preparation conditions. The a–b plane tunnelling seems to be sensitive to the exposure to air, and good junctions were obtained only by breaking the sample in vacuum.

Several a–b plane and c-axis tunnelling curves are shown in Fig. 1 (upper and lower panels, respectively). All of these measurements were taken at low temperature ($T \ll T_c$). The

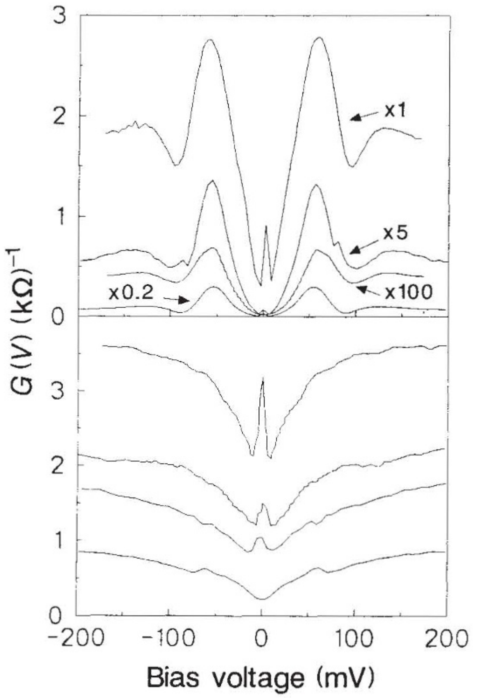

FIG. 1 Differential conductance, G, as a function of bias voltage, V, obtained from several break junctions at $T = 9$ K. Top, a–b plane; bottom, c-axis configuration.

junction resistances are in the range $R = 500\ \Omega$–$500\ k\Omega$, much larger than the contact resistance or sample resistance. In both cases a supercurrent is visible at zero bias, but only for the junctions with lower resistance. This current was suppressed by external magnetic field of ~1 kG. We assume that this current is due to the Josephson effect, although we did not observe the interference pattern typical of Josephson current in evaporated junctions with well defined geometry and uniform current distribution[1].

The temperature dependence of the tunnelling is illustrated in Fig. 2. For each temperature the conductivity is normalized to the arbitrary, but fixed (and relatively high) value at $v = 200$ mV. This was necessary to correct for the thermal expansion effects. (The normalization constant, G(200 mV), is nearly independent of the temperature up to 80 K.)

We want to call attention to several important features of the spectra presented in Figs 1 and 2. At low temperatures the zero-bias conductance is zero for tunnelling parallel to the a–b plane (if the pair-tunnelling contribution is subtracted), whereas it is finite for c-axis tunnelling. The a–b plane conductance exhibits a gap-like structure near $V = 55$ mV, but no well-defined structure is seen in the c direction. The a–b plane spectra become relatively smooth above T_c, whereas the c-axis curves continue to show temperature dependence. In fact, the c-axis tunnelling curves can be approximately fitted by an empirical formula, $G = G_0 \log(\xi/\xi_0)$, where $\xi = (eV)^2 + (\alpha k_B T)^2$ and G_0, α and ξ_0 are fitting parameters. Finally, at large bias the a–b plane tunnelling conductance decreases, but the c-axis conductance increases with increasing bias voltage.

In the superconducting state the a–b plane tunnelling is best understood in terms of a strong, temperature-dependent variation of the DOS, although fitting the data to the weak coupling BCS theory is clearly out of question (even if the gap $2\Delta = 3.5 k_B T_c$ is scaled to a higher value). Introducing finite lifetime for the Cooper pairs (as done by Dynes *et al.*[15]) does not help, either. Strong coupling calculations, like the one presented by Allen and Rainer[16], are being tested. The vanishing tunnelling conductance at zero bias unambiguously shows that at low temperatures the DOS at the Fermi level is zero. Thus the tunnelling results confirm an important aspect of the BCS theory. There is, however, no evidence for a fully developed BCS gap; the data indicate a nonzero DOS at energies different from the Fermi energy. Above the critical temperature the tunnelling conductance does not exhibit the 'V'-shaped curves seen for evaporated junctions[7], but it is similar to the point-contact measurements of Huang *et al.*[17].

To evaluate the c-axis tunnelling results, we recall that the tunnelling conductivity can be expressed in terms of an integral containing the tunnelling probability, the density of states and the Fermi function. In a somewhat simplified way, the shape of the low-temperature curves for c-axis tunnelling can be attributed either to the DOS having a strong energy dependence near the Fermi energy, or to scattering effects, introducing a nontrivial energy dependence into the transmission probability. Tunnelling to systems with localized electronic states, like amorphous $Ge_{1-x}Au_x$ (ref. 8), or amorphous Ge (ref. 9), belong to the first category. Junctions with magnetic impurities are good examples of the second category. Kondo-type scattering, observed for Cr-doped[10] and O_2-doped junctions[11], and discussed by Mezei and Zawadowski[12], introduces a logarithmic voltage and temperature dependence into the transmission probability, resulting in spectra similar to ours. Kirtley and Scalapino[13] recently obtained 'V'-shaped tunnelling spectra by considering inelastic scattering processes.

The first attempt to measure anisotropic tunnelling on high-T_c single crystals was by Kirtley *et al.*[18]. These authors, as well as Tsai *et al.*[19], concluded that in $YBa_2Cu_3O_7$ the gap is likely to be anisotropic. Ekino and Akamitsu[20] found a smaller gap in the c-axis configuration than in the a–b plane for $Bi_2Sr_2CaCu_2O_8$. A similar conclusion was reached by Briceno

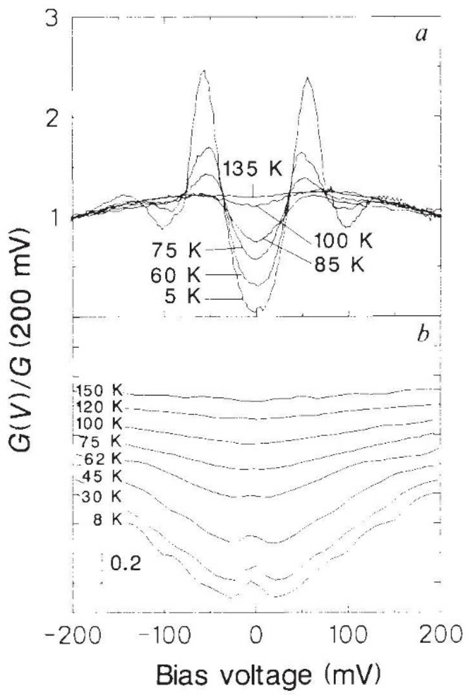

FIG. 2 Tunnelling conductance *a*, for *a–b* plane tunnelling; *b*, for *c*-axis tunnelling in $Bi_2Sr_2CaCu_2O_8$ for the temperatures indicated. The curves are normalized to the conductance at a bias voltage of $V = 200$ mV. Successive *c*-axis curves are shifted by 0.1 unit for clarity. All data in this figure were obtained on junctions prepared in vacuum at low temperature.

and Zettl[21]. Most of these measurements were made with a metallic tip in a point-contact configuration, where the direction of tunnelling is not very well defined, as the contact can actually penetrate the specimen[22,23]. In contrast, our study (Fig. 1) illustrates that although there are variations between tunnelling spectra belonging to the same class (*a–b* plane or *c* axis), the difference between the two classes is much more marked.

We should point out that in a point-contact or break-junction geometry, variations in the tunnelling spectra can arise because of the variations in the local DOS[24], as shown by tunnelling microscope studies[25,26]. In fact the sample may cleave preferentially between the BiO layers, and the *c*-axis tunnelling curves could measure the 'BiO density of states'. For our measurements, the total absence of the 0.1-eV insulating energy gap, seen by Hasegawa and Kitazawa[25] in the BiO layers, makes this unlikely.

We conclude that the tunnelling spectra parallel and perpendicular to the copper oxide planes are determined by entirely different microscopic parameters or microscopic mechanisms. The survey of the literature and our experience indicate that it is hard to realize pure *a–b* plane or *c*-axis tunnelling. In the strongly anisotropic copper-oxide-based superconductors it will be extremely difficult, if not impossible, to perform something similar to the 'classic' McMillan–Rowell evaluation of the tunnelling spectra[1,2] where variations of a few per cent in the tunnelling conductivity are attributed to electron interactions. This type of evaluation may have better chances for the cubic $Ba_{1-x}K_xBiO_3$ material[27]. □

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Structure and bonding in alkali-metal-doped C_{60}

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IT has been shown recently that M_xC_{60} (M = alkali metal) is metallic at 300 K for some M and *x* (ref. 1) and superconducts below 18 K for M = potassium[2]. These observations give further impetus to studies of the molecular[3] and solid-state[4] properties of fullerenes. Here we report on X-ray diffraction studies of the structure and bonding in alkali-metal-doped solid C_{60} (fullerite). Powder diffraction data obtained from equilibrium compositions of C_{60} doped to saturation with K or Cs show that the face-centred cubic lattice of pure C_{60} (refs 5–7) transforms to body-centred cubic at these doping levels, with a saturation composition close to M_6C_{60}. The rotational disorder of the fullerene molecules in pure C_{60} at 300 K is absent in the fully doped compounds.

Because our samples may be different from those of refs 1 and 2, a definite identification of the superconducting phase cannot be made at this time. No information was given on chemical composition or X-ray structure of the latter samples, and the conductivity and superconductivity measurements were performed mostly on nonequilibrium compositions. Both the normal conductivity and superconductivity were ascribed to the formation of a doped molecular crystal, analogous to 'ionic salt' intercalation compounds in which the host lattice and its electron states are largely unperturbed by the guest, and the metallic properties originate in delocalization (or intermolecular hopping) of transferred electrons. This implies that metallic character will be optimal at a composition K_3C_{60}, in which one delocalized electron per K leads to a half-filled conduction band derived from a threefold-degenerate molecular level[1,2]. This suggestion was justified by the observation that the 300-K conductivity first increases and then decreases with time of exposure to potassium vapour, on a timescale of about 4 h when the vapour temperature is held at about 75 °C. It was further suggested that metal atoms occupy vacant tetrahedral and octahedral sites in the f.c.c. lattice[1], thus maintaining the same close packing and intermolecular contact as in pure C_{60} (refs 5–7).

Our results support some features of such an intercalation analogy, but the equilibrium structural modifications on doping

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