

## PHYSICS

# Watching Rush Hour in the World of Electrons

Jan Zaanen

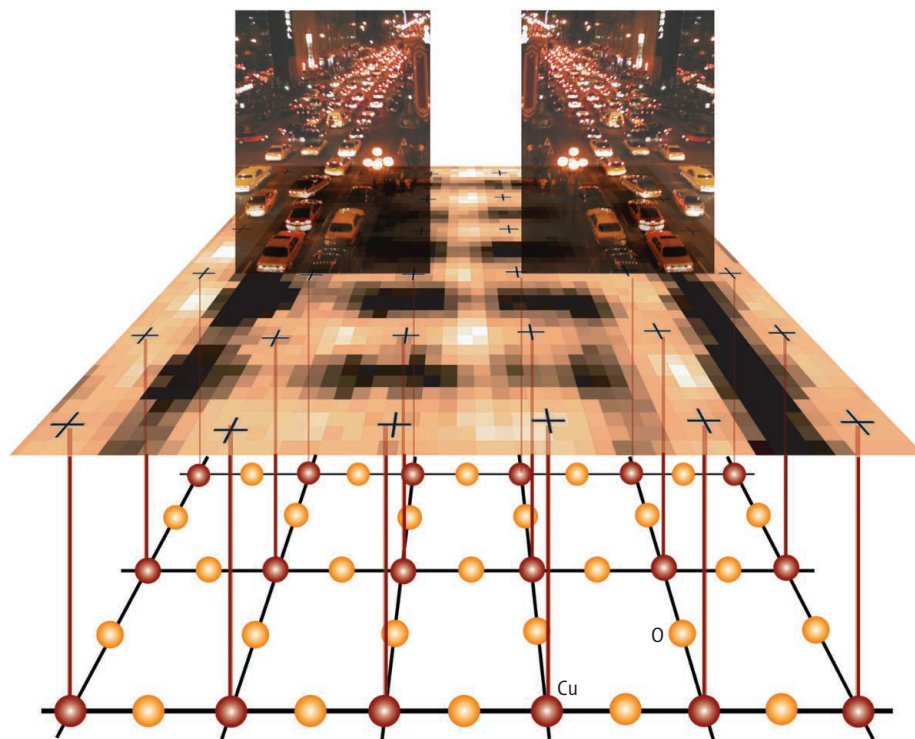
During the last decade, a revolution has been unfolding in our understanding of the behavior of electrons in solids. Quantum mechanics rules in this microscopic world, and researchers assumed that the smearing and averaging effects of the quantum motions would render this behavior exceedingly simple. In studying high-temperature ( $T_c$ ) superconductivity in copper oxides, however, physicists found instead that the electron systems in these materials were exceptionally complex. On page 1380 of this issue, Kohsaka *et al.* (1) present an experimental breakthrough, studying the electron system on the surface of copper oxide superconductors by means of scanning tunneling spectroscopy. By cleverly exploiting the effects of the electron interactions, they manage to probe the electron traffic directly. They discover a world of amazing richness, shaped by the quantum motions of the electrons forming complex spatial patterns.

A main effect of strong interactions in the classical world is well known to anybody living in a metropolitan area: When the density of cars becomes too high during rush hour, the traffic comes to a standstill. The same phenomenon should occur with electrons in solids, but the weirdness of quantum physics interferes. Electrons should execute continual quantum motions, and these are so violent in conventional metals and superconductors that the effects of the interactions are washed away. In this regard, the electron systems found in high- $T_c$  superconductors are exceptional. Due to the strong potentials exerted on the electrons by the crystal lattice of copper oxide planes, the quantum motions are hindered to a degree that the electron traffic might even get completely jammed. Copper oxides in their pristine state are thus insulators and, in order to turn them into (super)conductors, one has to remove electrons by chemical doping (that is, the addition of impurity elements).

The electron motions in these doped cuprates can be viewed as quantized stop-and-go traffic. Stop-and-go traffic in our world tends to develop complex collective patterns,

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An improved imaging technique reveals that electrons in a material can suffer gridlock like cars in a city. This may help researchers understand the mechanism by which currents flow without resistance in superconductors.



**Traffic patterns.** Scanning tunneling spectroscopy can directly probe the spatial distributions of the electron motions in the copper oxide layers of a high- $T_c$  superconductor. The patterns can be viewed as a quantum analog of stop-and-go traffic, self-organizing into one-dimensional highways where the electron traffic flows relatively freely, separated by severely jammed areas. Locations of copper and oxygen atoms are shown below the image of electron flow.

and something similar happens with the electrons. In calculations, physicists found that electrons moving around in the copper oxide planes tend to arrange themselves in one-dimensional “highways” where they move rather easily, surrounded by insulating domains (2), and in recent years experimental support was found for the existence of such stripe patterns (3). There are indications that they occur in good superconductors as fluctuating patterns (3, 4), while in some cuprates they actually come to a standstill, likely due to imperfections in the crystal lattice having an effect similar to roadwork on our highways. These static stripes are clearly observed in both neutron-scattering (3) and resonant x-ray-scattering experiments (5), but these experiments only pick up average properties of the stripes. Researchers would like to view them in real space (as opposed to the reciprocal space of diffraction), and this is exactly what

Kohsaka *et al.* claim to have accomplished.

How do Kohsaka *et al.* manage to probe these electron structures? They use scanning tunneling spectroscopy, a technique that measures the quantum mechanical probability of adding or removing an electron at a specific location at a given energy. In strongly interacting electron systems like those of the high- $T_c$  superconductors, this probability is very hard to interpret. Kohsaka *et al.* have found a way around this difficulty, based on a clever but simple idea of Anderson and Ong (6) that exploits the effects of the strong electron-electron interactions. To understand the essence of the idea, one just needs freeway experience: To merge from the ramp on a freeway with stop-and-go traffic requires patience, whereas it is a relief to spot an exit sign. The same effect occurs in the stop-and-go electron system: It is much easier to remove electrons than to add them. To obtain the overall probability of either

removing or adding an electron, one has to simply integrate the tunneling current for a positively charged tip (pulling electrons out) and for a negatively charged tip (injecting electrons) over a sizable voltage range at a given location, and by taking the ratio of these quantities one obtains a map of the electron traffic.

As shown in the figure, the bright areas are where the electrons move around relatively freely, and the dark regions are where the electron traffic is jammed. The image has atomic-scale resolution, and it is clear that the mobile electrons have a preference for oxygen over copper. Zooming out to the nanometer scale, one clearly discerns the stripes, the “rivers of charge” separated by insulating regions, while on an even larger field of view these turn into a

glassy pattern (1), illustrating the sensitivity of the stripes to disorder in the crystal lattice (3). There is actually much more going on in these images than is apparent at a first glance, and the million dollar question is whether these subtleties reveal anything about the origin of superconductivity at high  $T_c$ . This is still as much a mystery as it was 21 years ago when it was discovered (7, 8). It is believed that, as in normal superconductors, the electrons bind in pairs that subsequently undergo Bose condensation that causes the superconductivity. It might well be that the images obtained by Kohsaka *et al.* are about electron pairs coming to a partial standstill, instead of the electrons themselves. When I stare with my trained eyes at the images I see these pairs everywhere. This might well be

an illusion, but by combining the present technique with the energy-resolved spectroscopic information, it should be possible to generate hard evidence for the reality of these pairs.

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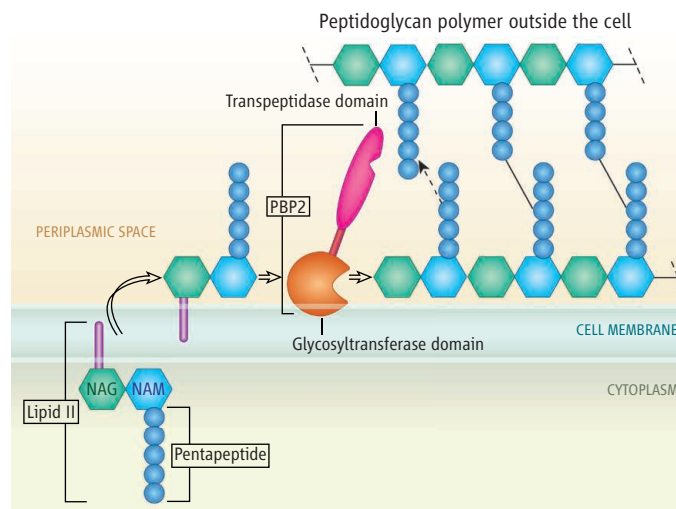
## BIOCHEMISTRY

# A New Target for Antibiotic Development

Gerard D. Wright

The discovery and clinical development of penicillin ushered in the modern antibiotic era and stimulated the discovery of the antibiotics in current clinical use. Some 80 years after their discovery, penicillins and related antibiotics (collectively called  $\beta$ -lactams) remain clinically useful. Nevertheless, the remarkable ability of bacteria to develop resistance to  $\beta$ -lactam and other antibiotics means that there is a continued need for new antibiotic targets and new antimicrobial agents. On page 1402 of this issue, Lovering *et al.* (1) report the crystal structure of a bifunctional bacterial membrane protein that provides target sites not only for  $\beta$ -lactams but also for new antibiotics.

Penicillin and other  $\beta$ -lactam antibiotics target several bacterial enzymes, collectively termed penicillin-binding proteins (PBPs). PBPs are necessary for the growth and maintenance of the peptidoglycan layer, which forms part of the bacterial cell wall and protects the cell from osmotic stress. Inhibition of peptidoglycan biosynthesis and of its controlled



breakdown (for example, to enable partition of the cell wall during cell division) therefore inhibits cell growth. Because the peptidoglycan polymer is ubiquitous and essential to bacterial life, its assembly and maintenance are targets for many antibiotics (2).

The peptidoglycan consists of a backbone chain of repeating two-sugar units (called NAG and NAM) and a pentapeptide chain bound to each NAM (see the figure). The NAG-NAM-pentapeptide core (called lipid II) is synthesized in the cell and tethered to the cell membrane by a lipid linker. Lipid II is then transferred from the inside of the cell to the outside, where membrane-associated glyco-

The crystal structure of a bacterial membrane protein may guide the development of new antibiotics that interrupt a previously neglected molecular target.

**Beyond penicillins.** Bacteria use a peptidoglycan layer to protect themselves from osmotic stress. Synthesis of this layer proceeds in several steps. First, lipid II is synthesized in the cell. It is then transferred to the outside, where it is added to the peptidoglycan polymer by membrane-associated transglycosylase enzymes. Finally, the polymer is cross-linked via interstrand peptide bonds catalyzed by transpeptidase enzymes. Lovering *et al.* now report the three-dimensional structure of a bifunctional transglycosylase-transpeptidase. The structure should aid development of new antibiotics targeting the transglycosylation domain.

yltransferases assist in grafting it onto the polymer. Transpeptidases catalyze the formation of peptide bonds between polymer strands, thereby making the wall more rigid. These tasks are performed by bifunctional enzymes that contain glycosyltransferase and transpeptidase domains; the latter are sensitive to  $\beta$ -lactams.

Previous studies of the final steps of peptidoglycan biosynthesis have tended to focus on the transpeptidase stage of assembly. However, the inhibition of transpeptidase activity by penicillins is only half the story, and the glycosyltransferase activity of the bifunctional enzymes is an excellent target for the development of new antibiotics (3, 4).

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