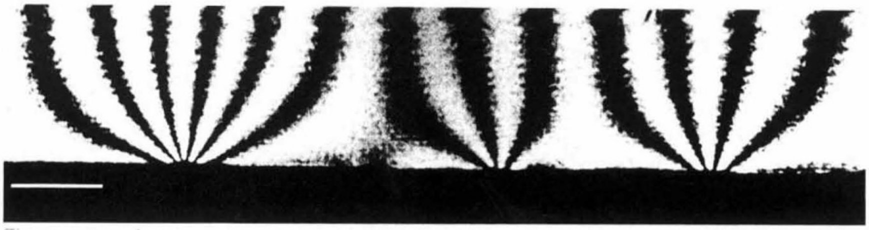
Seeing the unseeable

The ability to move atoms and molecules with the STM has perhaps diverted attention from the equally wonderful possibilities for 'seeing', and more broadly, sensing, offered by this microscope and its relations. Heinrich Rohrer (IBM Zürich Research Laboratory) surveyed the broad sweep of these possibilities, pointing out that the range of possible interactions between tip and sample (van der Waals, adhesive, magnetic and electrostatic, to name a few) offers both opportunities and potential problems. In principle, one can isolate any property of interest and measure it locally: under the broad heading of magnetism, for example, one can use the magnetic valve effect (in which the tunnelling current is sensitive to the electron polarization), magnetic force microscopy (with a magnetized tip), or magnetic resonance microscopy. Any of these techniques can also be combined with spectroscopy — for example, one might inject polarized electrons from the tip, and measure the emission of polarized photons. But Rohrer cautioned that the sheer number of interactions makes it hard to be sure that one is really looking at the interaction of interest, and one must also ensure that the probe itself doesn't interfere with the experiment one is trying to perform.

Akira Tonomura (Hitachi Advanced Research Laboratory) reminded the audience that the STM is not the only way to create atomic-scale images. The availability of coherent electron beams, produced by field emission from a pointed tungsten tip, has led to the technique of electron holography, for both high-resolution imaging and electron interferometry. Tonomura illustrated the use of reflection interferometry to measure surface topography with a resolution of less than 0.01 nm. Like the STM, however, the technique can do far more than simply sense topography. Thanks to the Aharonov–Bohm effect, the phase of an electron wave is sensitive to the presence of an electromagnetic field: the fringes in an interference micrograph appear along magnetic lines of force, with a separation of one flux quantum between adjacent fringes. Following the use of electron holography to demonstrate definitively the existence of the Aharonov–Bohm effect, Tonomura has used the technique to image flux lines in superconductors — providing direct evidence for flux-line pinning, and other aspects of flux-line dynamics induced by thermal excitations or interactions with the supercurrent. Having seen Tonomura's videotape of flux lines dancing across the surface of a superconductor (see figure), one is inclined to believe him when he says, "with this technology, even thought experiments will be possible". □



Electron interference micrograph showing bundles of flux-lines emerging from the surface of a superconducting lead film. Scale bar, 2 μm.

nevertheless form bilayer vesicles in just the same way as phospholipids. This propensity is, however, determined by the redox state of the iron — electrochemical oxidation of the Fe^{2+} to Fe^{3+} causes vesicles to form, while reduction breaks them down again (J. C. Medina *et al. J. Am. chem. Soc.* **113**, 365–366; 1991). Gokel has also demonstrated redox-switchable binding of metal ions in a ferrocene derivative in which the two cyclopentadienyl rings are bridged by several tertiary diamine loops (nitrogens joined by aliphatic chains), leaving a rigid cavity between the nitrogen donor atoms. The bound metal ion sits next to ferrocene's Fe^{2+}, and is therefore expelled when the iron is oxidized to give a positively charged ferrocenium species.

One might also regard as a kind of mechanical switching the structural changes that binding of substrate to receptor can initiate. Particularly suggestive of this mechanical response was Gokel's 'cleft-like' receptor in which the rotational freedom of ferrocene's aromatic five-carbon rings around the iron 'ball bearing' is exploited to build receptors with arms that swing around to lock their substrates in place. Of an entirely different nature is the mechanical switching of toroidal molecules threaded on a linear chain — the so-called rotaxanes. Fraser Stoddart's group in Sheffield has proposed that their rotaxanes, comprising cyclic bipyridinium units threaded on linear hydroquinols or vice versa, might be assembled into a 'molecular abacus'; a variant presented by Gokel was a cyclodextrin on a hydrocarbon chain capped with ferrocene and a sulphonate group.

Masuo Aizawa (Tokyo Inst. of Technology) suggested that mechanical switching also lay behind the transfer of conformational change between two proteins covalently linked by a kind of molecular transmission shaft. Binding of a calcium ion to calmodulin converted from an inert to an active form the phosphodiesterase enzyme to which it had been attached by a covalent bond.

To some extent one might regard these molecular-based switches as components in search of a device. But as an example of a practical device that relies on engineering and interactions at the molecular scale, the biosensor provides arguably the best example currently on the scene. The earliest glucose sensors, developed in the 1960s, were little more than electrochemical oxygen sensors that depended on the immobilization of the enzyme glucose oxidase at the electrode surface. But Aizawa discussed possibilities for improving signal transmission at the molecular level. He showed that the electrical connection between the enzyme and the electrode can be enhanced by attaching to the electrode surface molecular wires (in this case conjugated polypyrrole molecules), the free ends of which may find access to the redox site on the enzyme.

Materials design

Fullerenes, inevitably, surfaced in many contexts: C_{60} is perhaps the perfect nanoscale construction material, a structural unit itself only marginally smaller than a nanometre. But Richard Smalley considers the graphitic microtubules reported recently (S. Iijima, *Nature* **354**, 56–58; 1991) to be of potentially equal importance; calculations indicate that some may be semiconducting and that their perfect crystallinity will make them the strongest fibres known. It is far from nanotechnological oversell to imagine welding these girders into rigid superstructures with an electron beam (perhaps having first arranged them with the STM?). The hierarchical structure of these frameworks, the basic elements of which are themselves built from the graphite 'chicken-wire' mesh, should imbue them with some of the advantages that hierarchy bestows on natural substances such as bone, an issue addressed by Paul Calvert (Univ. Arizona).

Among these superior properties, said Calvert, are toughness, damage tolerance (local failure need not lead to global breakdown), repairability and ease of further growth. Bone provides perhaps the classic example: the poros-