the nanomechanical resonance peak — a plot of the detected oscillation amplitude, which is proportional to the device current versus driving frequency — when the resonator was driven into the nonlinear regime[2]. Rather than this resonance peak being symmetric, as it is in the linear regime, it is split into two peaks, with the higher frequency peak being much sharper than the lower frequency one. This splitting is caused by the interplay between nonlinearity in the detection method and nonlinearity in the relationship between the vibration amplitude and drive frequency. For large enough vibration amplitudes, the change in the capacitance of the nanotube–gate system can change the value of V_g at which the Coulomb peaks occur: these changes can be large enough to tune the device to a Coulomb valley during part of each oscillation cycle, which leads to a decrease in the current. The detected amplitude therefore gets smaller as the vibration amplitude increases in this regime. This produces a dip in the detected amplitude at the frequency were the peak should be, producing a double peak structure. Meanwhile, the vibration amplitude shows a gradual rise, followed by an abrupt drop-off as the device switches from one stable vibration mode to another. The abrupt drop-off of the vibration amplitude strongly sharpens the higher frequency peak, producing a large and enhanced effective Q.

Gary Steele and colleagues at the Delft University of Technology also observe nonlinearities, and deduce that the electrostatic forces dominate the behaviour in this regime[1]. Furthermore, they are able to make their nanotubes oscillate by passing a d.c. current through the nanotube. Although the fluctuating force caused by the electrons hopping on and off the nanotube might be expected to excite a small amount of vibration, the strong coupling between the electronic and mechanical properties of the nanotube leads to very large vibrations, consistent with recent theoretical predictions[5]. This impressive demonstration relies on two key factors in their experiment: the extremely low mass of the nanotube compared with nanofabricated resonators, and the high value of Q (~10^5) for their device. Theorists have also predicted that the noise in the electrical current through the nanotube during such driven vibrations will exceed the usual shot-noise value[5]. It would be very interesting to search for this behaviour in future experiments.

The work of the Delft and Barcelona–Chalmers teams demonstrates the kinds of surprising behaviour that can emerge in nanomechanical systems, opening up many possibilities for future work. The high values of Q may, for example, allow very small masses or forces to be detected. Furthermore, at the lowest temperatures reached in the experiments, the nanotube was probably very nearly in its quantum mechanical ground state for vibrational motion. This may open up a number of possible experiments such as the creation of Schrödinger's cat-like mechanical states that can be modified or probed by electron tunnelling. ❐

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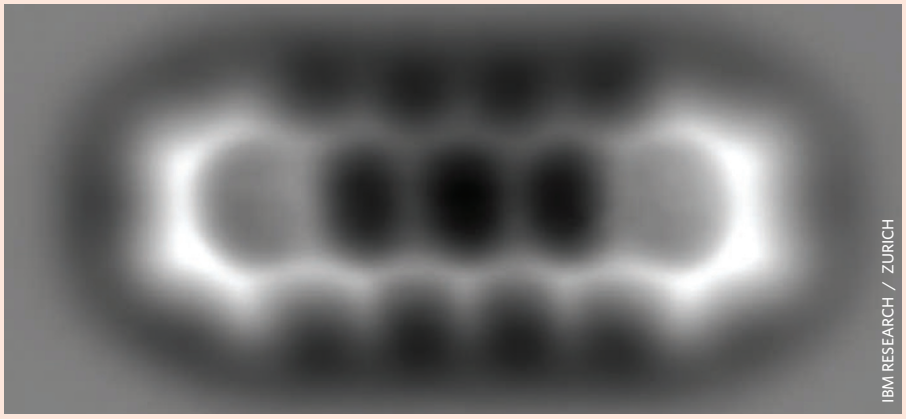
PROBE MICROSCOPY

A closer look at the atoms in a molecule

The atomic force microscope (AFM) was invented five years after the scanning tunnelling microscope (STM), but it has since become the most widely used form of scanning probe microscopy. However, the STM has remained the pre-eminent instrument for imaging and manipulating structures on the atomic scale. Now, researchers at IBM's Zurich Research Laboratory and Utrecht University have shown that an AFM operated in non-contact mode can surpass the imaging capabilities of its elder sibling by resolving the atoms within a molecule adsorbed on a surface (*Science* **325,** 1110–1114; 2009).



Leo Gross and colleagues examined molecules of pentacene ($C_{22}H_{14}$) adsorbed on a copper(111) surface and on a sodium chloride film. With the STM, resolving atoms within an adsorbed molecule is difficult because the tunnelling current is sensitive to the local electron density of states near the Fermi level, and this density of states extends over the entire pentacene molecule. However, by adding a carbon monoxide molecule to the tip of an AFM, and by probing the short-range chemical forces, Gross and colleagues were able to resolve the atomic positions and bonds inside the pentacene molecules.

The AFM image above, which measures 27.5 Å across, clearly shows the five fused benzene rings in the pentacene molecule. To take the image Gross and colleagues scanned the AFM, which was oscillating with an amplitude of 0.2 Å, at a constant height above the surface and measured how the force on the tip changed with position.

By comparing the experimental data with the results of density functional theory calculations, the researchers found that Pauli repulsion forces are the origin of the atomic resolution.

OWAIN VAUGHAN