Quantum Constructions

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In a visionary speech entitled "There's Plenty of Room at the Bottom," Richard Feynman speculated on the fascinating properties of matter made by arranging "the atoms one by one the way we want them" (*1*). The possibility of atomically engineering artificial structures has recently come within our grasp with the scanning tunneling microscope (STM) and related scanning probe technologies. Images of surface atoms are now common, and more recently, the manipulation of atoms on a surface has been demonstrated (*2*).

In addition to the rich surface science enabled by scanning probe microscopies, these tools have now given researchers a tantalizing and unprecedented ability to engineer systems whose properties are dominated by quantum mechanical phenomena. On page 218 of this issue, Crommie *et al.* (*3*) give a pleasingly illustrative example of quantum size confinement realized by atomic manipulation and a textbook picture of electron wavefunctions that exist within such structures.

Since approximately the mid-1970s, before the STM, low-dimensional confinement structures called quantum wells could be made by molecular beam epitaxy and metal-organic chemical vapor deposition. High-energy barriers cladding the quantum well confine the electrons into a two-dimensional (2D) sheet, creating particle-in-a-box quantization in the thin epitaxial direction. Though these techniques have atomic control in the epitaxial growth direction, they do not allow us to artificially structure materials in the remaining two lateral directions, which would create total quantum confinement.

A variety of techniques that achieve lower dimensional structures—quantum wires (1D) and quantum dots (zero-dimensional)—have been attempted with varying degrees of success (*4–6*). Combining 2D epitaxial technology with nanometer-scale lithographic techniques, researchers have been able to carve out or electrostatically squeeze thin lines and dots. The quantum confinement of the electrons in these structures is reflected in the energy states of the wire or dot, measured by optical or electronic techniques. An unambiguous demonstration of the quantum confinement would be the spatial mapping of the standing-wave patterns of the electrons inside the structure; until now, however, the electron wavefunctions of low-dimensional structures could only be derived by inference.

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Researchers at the IBM Watson Research Center (*7*) and the IBM Almaden Research Center (*8*) have discovered that they can directly measure by STM the wave patterns of electrons confined to the surface of a metal. Although not as precise a confinement as an epitaxial quantum well, the surface state electrons are nonetheless confined in a quasi-2D sheet to the surface. This is in fact an advantage because the electron density on the surface can be directly imaged by STM. Electrons propagating along the surface, as waves, would occasionally encounter random obstacles: defects or atomic steps in the surface. Such obstacles would cause the electron waves to partially reflect, creating rippled interference patterns. These spatial oscillations are a direct measurement of the electron density caused by quantum mechanical interference; in other words, a spatial map of the electron wavefunction.

If one can measure electron patterns for electrons as they reflect from these accidental boundaries, can one use the same STM to manipulate atoms and construct an engineered confinement structure? Crommie *et al.* (*3*) have done just that. For their experiments, they used an atomically flat Cu(111) surface upon which they deposited a small number of Fe atoms. They found that the Fe atoms act as strong potential barriers to the surface state electrons. The electron density map in the vicinity of an Fe atom exhibits a concentric rippled interference pattern owing to the reflected surface state electrons.

These Fe atoms can now be used as the building blocks of designer structures, in which electron interference is determined by the placement of the potential barriers. The Fe atoms were placed by atomic manipulation techniques into an orderly structure on the Cu(111) surface, in this case a circular ring with a radius of 7 nm. Combined together, the potential of the 48 individual Fe atoms presents a hard, cylindrical lateral potential barrier to the surface state electrons, creating a circular quantum "box," a common problem found in quantum mechanics textbooks. The structure is, in essence, a quantum dot; in the terminology of Crommie *et al.*, a quantum corral. It has the distinct advantage over previous semiconductor constructions of quantum dots because the electron density can be directly accessed by the STM tip.

Because the ring is approximately the same length scale as the electron de Broglie wavelength, and the electrons do not lose phase memory (that is, they do not scatter) over this distance, it is possible to observe coherent interference of the electron waves in the corral. Indeed, when the electron density inside the corral is measured, distinct circular ripples are observed, reminiscent of water waves in a circular pool. The measured density is in good quantitative agreement with the expected Bessel-function solutions one expects for the circular quantum box problem. For the student of quantum mechanics, this is a pleasantly aesthetic and convincing visual demonstration of quantum mechanical wave interference.

This demonstration opens up a fascinating new realm of fundamental physics. A plethora of enticing quantum-confinement structures, manufactured with atomic precision, can be imagined. The particle-in-a-box wavefunctions for different geometrical patterns, regular (squares, ellipses) or "chaotic," can be mapped; indeed, the size, shape, and symmetry of the confining potential can be tuned to engineer the wavefunction of the dot and study atomic physics of artificial designer atoms previously inaccessible in nature. The wavefunctions for multibranched wave-interference structures, such as Aharonov-Bohm rings (a two-branched ring for which the wavefunction phase between the branches is modulated by a magnetic field) or electron-waveguide structures, can be investigated. Arrays of periodic structures, lateral surface superlattices, and the resultant bandstructure can be created and manipulated. The quantum-corral technique provides an exciting mini-laboratory for a range of exciting condensed matter mesoscopic physics.

References

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