Near-Field Imaging with Sound: An Acoustic STM Model

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Near-Field Imaging with Sound: An Acoustic STM Model

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The invention of scanning tunneling microscopy (STM) 30 years ago opened up a visual window to the nanoworld and sparked off a bunch of new methods for investigating and controlling matter and its transformations at the atomic and molecular level.[1] However, an adequate theoretical understanding of the method is demanding; STM images can be considered quantum theory condensed into a pictorial representation. A hands-on model is presented for demonstrating the imaging principles in introductory teaching. It uses sound waves and computer visualization to create mappings of acoustic resonators. The macroscopic simile is made possible by quantum-classical analogies between matter and sound waves. Grounding STM in acoustic experience may help to make the underlying quantum concepts such as tunneling less abstract to students.

Challenging mechanistic imagery

STM combines classical engineering with quantum physics. The classical part refers to scanning surfaces at atomic scales with a tip-shaped probe that ends in a single atom. Its motion is controlled by a piezoelectric drive. Quantum physics comes in by measuring the tunnel current between tip and surface. Many teaching models demonstrate the method by scanning macroscopic structures through mechanical contact or magnetic forces, using marbles or table tennis balls to represent atoms.[2,3] The mechanical models neglect the special quantum nature of the interaction between tip and surface atoms. Moreover, they support naive beliefs by attributing macroscopic properties such as a well-defined shape to atoms.

Similar views are also favored by the photo-realistic character of popular STM images. They create the impression of a relief map that accurately reflects the topographic features of a nanolandscape. The atomic signatures are visually enhanced by adding color, shades, and reflectance. As these emergent classical properties do not exist on the level of individual atoms, they tend to confuse inexperienced spectators. In some images, atoms seem to sit on a smooth plane like tiny heaps of matter. Contrary to the naive views, the structures do not mechanically display atoms. They correspond to corrugations in the electronic density of states that modulate tunneling probability.

Is it possible to ground the abstract imaging principles in concrete experience from daily life? The main problem in devising a teaching model is to find a classical system that reproduces relevant features of tunneling. This task might appear impossible at first sight as tunneling is considered a purely quantum effect. However, classical counterparts to tunneling exist in the domain of waves.[4]

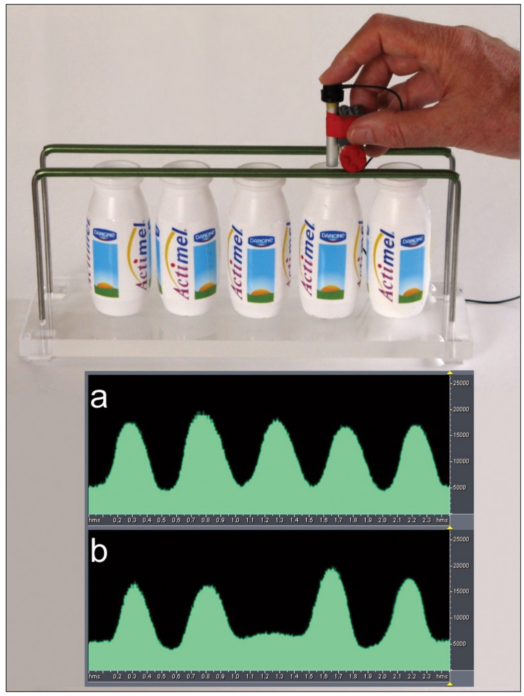

Fig. 1. Acoustic responses from scanning a row of yogurt bottles. In (a) the signals of five empty bottles are shown. In (b), the middle bottle is partly filled up with water.

Quantum tunneling and classical waves

Electrons can tunnel between occupied and empty electronic orbitals of the approaching tip and surface atoms. In visual parlance, the tunneling current is a product of the wave-like properties of electrons that allow electron "clouds" to extend into classically forbidden regions. Therefore, tunneling begins before a full mechanical contact is established. The current strength depends on the overlap of the electronic states and increases exponentially by decreasing the distance between tip and surface.

Depending on the operation mode, STM images provide different views of the scanned systems by displaying structural aspects (topographic mode) or dynamical aspects (spectroscopic mode). In the topography mode, the tip is scanned across the surface at a constant tunneling current. This is achieved by adjusting the distance between tip and surface through a feedback mechanism. The tip can follow the apparent surface topography closely because the tunneling current is highly sensitive to the distance. In the spectroscopy mode, the distance between probe and surface is kept constant. The voltage dependent variations of the tunneling current at fixed probe positions reflect the energy dependence of the local density of states.[5]

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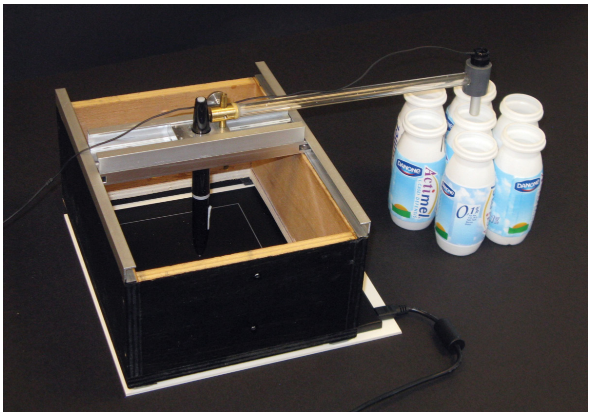

Fig. 2. A two-dimensional acoustic scanning device that collects data for computer visualization.

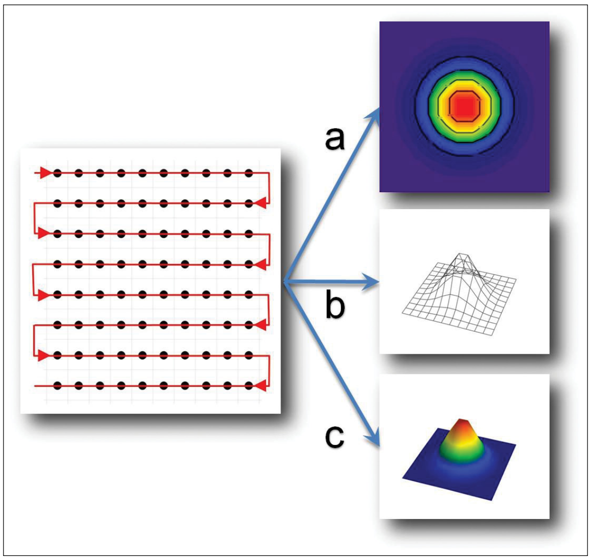

Fig. 3. Transforming the sound field data matrix into different visual representations: (a) contour plot, (b) mesh plot, (c) three-dimensional graphical rendering.

Tunneling is not restricted to matter waves. It can be simulated with classical waves, and even sound waves are appropriate! In classical language, the matching of energies and the overlap of electronic probability distributions of probe and surface states correspond to resonant processes. The resonance analogy provides an intuitive access to the subsequent acoustic scanning method, which is shown to be analogous to STM spectroscopy.

Hearing and localizing resonances

We are able to trace a sound source in the near field when it passes by one ear. We rely on acoustic spectroscopy to recognize a voice or the timbre of musical instruments. Thus, the capabilities of STM to locate atoms and to probe into their dynamics by spectroscopy can be grounded in acoustic experience. We start with a hands-on approach and use a sound probe to investigate acoustic resonators such as open bottles or cans. Figure 1 demonstrates the principle with a one-dimensional device for manually scanning a row of yogurt bottles.

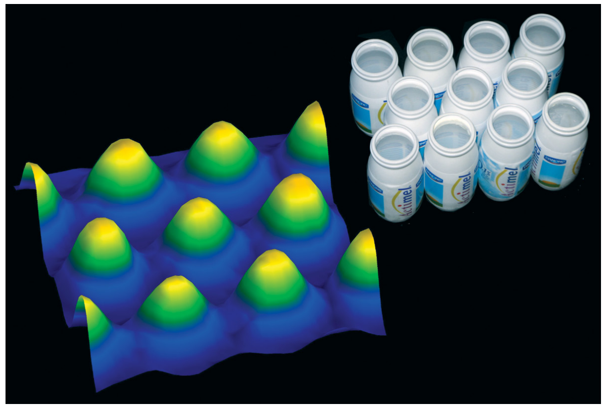

Fig. 4. Acoustic image and photo of 11 yogurt bottles.

The probe is constructed by extending an earphone capsule with a metal tube. It is attached to wheels from a Lego set in order to ease the scan. Two rails guide the motion. The probe is connected to a frequency generator and tuned to the first resonance of the bottle ($f \approx 2.4$ kHz). It is possible to find the position of the resonators by listening. The loudness of the resonant mode increases as the probe approaches the bottle's mouth. The sound probe can be turned into a measuring device by connecting a microphone to a bore in the tube's wall. Thus, a simple acoustic impedance probe is created. It injects a constant acoustic flow and picks up the local variations of sound pressure.[6]

Figure 1(a) shows the probe signals from an array of five bottles scanned manually at a constant rate. Each bottle is identified by a maximum response. This compares to locating individual atoms in STM. The spectral selectivity of the acoustic probe can be demonstrated by detuning one of the resonators. The third bottle in Fig. 1(b) is partly filled with water. It is not displayed because of the resulting frequency mismatch. The resounding bottles can be considered an analog of the resonating electronic orbitals of atoms. Tuning the acoustic frequency corresponds to choosing a suitable voltage in tunneling spectroscopy. It probes into the local density of electronic states at the corresponding energy. In this way, it is possible to detect and visually present specific atoms while others are hidden.

Two-dimensional acoustic mapping

The demonstration model is converted into a two-dimensional mapping device by using a graphic tablet as position sensor (Fig. 2). An *X-Y* table facilitates the scanning motion of a pen. Its position is sensed by the tablet below. The pen is grabbed and moved manually to create the scans. Its position is transmitted to a computer via USB while the microphone input collects the probe signals. As the pen is rigidly coupled to the acoustic probe, a two-dimensional record of the sound power at the probe tip is created. A computer program stores the sound field data from sequential scans point by point and line by line in a two-dimensional array. Figure 3 shows the visualization process schematically. The data matrix is transformed into different styles of visual presentations by using conventional programs such as Excel or SigmaPlot. Their graphical style galleries include three-dimensional renderings to create spatial views of the structures.

The sound field from scanning a hexagonal array of 11 yogurt bottles is shown in Fig. 4. The agreement with STM images is startling. An unbiased observer cannot tell if resonating bottles or atoms are presented. In contrast to atoms, it is possible to compare the visualizations with the "real" system. The clash with naive pictorial realism is evident. The "hills" do not stand for tiny heaps of hard inert matter. Instead, they indicate the presence of resonating dynamical systems. The maxima are displayed in the middle of the acoustic cavities where coupling with the lowest resonance is optimal.

Imagery, analogies, and critical realism

The acoustic STM model exploits the similarities between the scattering of sound and electron waves. The tunneling probability of electrons at a given energy depends on the local density of states. The latter can be measured by the differential STM current ($\Delta I/\Delta V$) at the corresponding voltage. This is equivalent to an impedance measurement of electron waves. The sound probe detects the local acoustic impedance. In this analogy, the acoustic power corresponds to the particle current, which in turn is dependent upon tunneling probability.[7] The acoustic power is proportional to the square amplitude of sound pressure while the quantum mechanical probability of detecting a particle is given by the square amplitude of the wave function.

By this "exact" analogy, the acoustic scanning model illustrates classical imaging principles that also apply to the quantum world. The acoustic impedance probe is able to locate resonating entities and to investigate their modes by spectroscopy. The scans do not provide further information. Therefore, it is obvious that only certain aspects of a more complex reality can be displayed. The analogy with matter waves shows that these limitations exist in principle and clarifies essentials of imaging atoms in STM. Atoms are conceived as dynamical entities that reveal their existence via electronic scattering processes. Thus, a thorough reflection of the imaging experiments may help to foster a critical realistic attitude with respect to pictorial representations of the invisible nanoworld.

Near-field imaging beyond diffraction limits

The acoustic model reveals another remarkable property. It uses a wavelength of $\lambda \approx 15$ cm to detect structures with a precision of 1 cm or even less. This is achieved by a near-field imaging scheme. In conventional far-field imaging, the resolving power is limited by diffraction. The resolution of an optical microscope is given by the Abbé criterion. It restricts the minimum distance Δx between two separable point sources to the order of $\Delta x \approx \lambda/2$. Near-field imaging by scanning overcomes the diffraction limit and allows the detection of structures much smaller than the wavelength. Although optical near-field methods were already described much earlier, they required the spark from electronic near-field imaging in STM that initiated the further development of optical techniques. At present, many novel schemes for optical nanoscopy are devised.[8] These new tools of optical super-resolution microscopy provide detailed views of the molecular machinery in living cells and open up fascinating new ways to explore life at the nanoscale level.

The present experiments clarify the nature of STM images and demonstrate the potential of near-field imaging to resolve structures much smaller than the wavelength. They complement the theory-laden interpretation of STM images by a transparent and intuitive hands-on approach. Strengthening intuition, promoting model-based knowledge, and bringing life to abstract theoretical concepts is crucial for a deeper understanding of the nanoworld and for exploiting its creative powers in future technologies.

Acknowledgments

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