Scientific Accomplishments: Instrumentation Research, Metrology, and Standards for Nanotechnology (PCA 4)

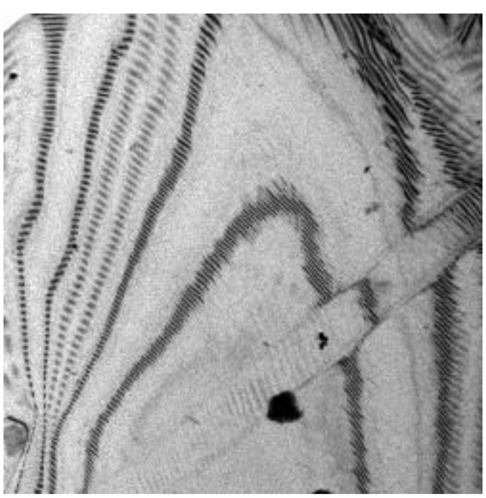
4D Electron Microscope for Directly Visualizing Atomic-scale Motion

A breakthrough technology allows, for the first time, the real-time visualization of fleeting changes in the structure and shape of matter barely a billionth of a meter in size. The new technique, named four-dimensional (4D) electron microscopy, was developed at the Caltech Physical Biology Center for Ultrafast Science and Technology under the direction of Nobel Prize-winner Ahmed Zewail.

Researchers can observe the static structure of objects with resolution better than a billionth of a meter in length using electron microscopes, which generate a stream of individual electrons that scatter off objects to produce an image. Zewail and his colleagues introduced time into high-resolution electron microscopy by releasing electrons at specific time intervals and precisely controlling their trajectories. Each electron results in a still image, and the sequential images generated by millions of electrons can be assembled into a digital movie of atomic scale motion.

Zewail's team used 4D electron microscopy to observe the behavior of the atoms in extremely thin sheets of graphite. The layers of carbon atoms in graphite move in a unique and coherent way on the femtosecond timescale; on the picosecond scale, the graphite nanosheets produce sound waves. Researchers directly visualized the elastic movements of the sheets and determined the force holding them together. They also visualized the changes in a nanometer-thick graphite membrane on a timescale up to a thousandth of a second. After being heated, the carbon atoms vibrated randomly, but over time the oscillations of the individual atoms became synchronized into a heartbeat-like "drumming."

This technique for directly visualizing atomic-scale motions will enable greater understanding of structural, morphological, and nanomechanical phenomena. It can also be used for biological imaging of cell components, such as proteins and ribosomes.



Nano-drumming of graphite, visualized with 4D microscopy. (Nano Letters; image produced at Caltech)

O.-H. Kwon, B. Barwick, H.S. Park, J.S. Baskin and A.H. Zewail. Nanoscale Mechanical Drumming Visualized by 4D Electron Microscopy, *Nano Lett*. **8**, 3557 (2008).

B. Barwick, H.S. Park, O.-H. Kwon, J.S. Baskin, and A.H. Zewail. 4D Imaging of Transient Structures and Morphologies in Ultrafast Electron Microscopy, *Science* **322**, 1227 (2008).

Patents or other steps toward commercialization: A patent on the conceptual framework of this approach was granted to the California Institute of Technology (Caltech) in 2006.

Contributing Agencies: Air Force Office of Scientific Research, NIH, and NSF