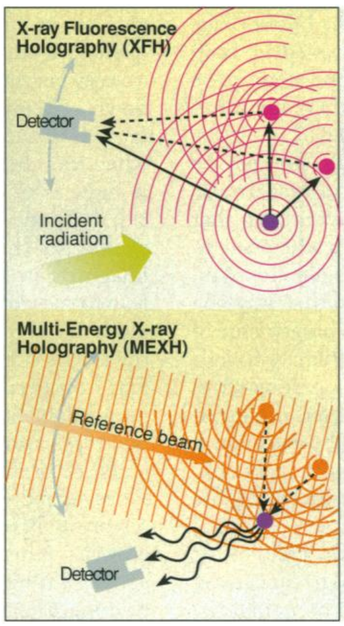
SOLID-STATE PHYSICS

Two Versions of Holography Vie to Show Atoms in 3D

In 1948, Dennis Gabor had an idea nearly 50 years ahead of its time. The Hungarian-born physicist had laid the theoretical groundwork for holography—a technique for making three-dimensional images from the interference patterns created when beams of coherent light or other radiation are shined on an object—and he was already thinking ahead. He believed his invention could provide direct, three-dimensional portraits of atoms.

Gabor won the 1971 Nobel Prize in physics for making holography possible, but he never saw it applied on an atomic scale. The reason: It required sources of intense, coherent x-rays and a way to trace x-ray signals from specific atoms in the sample, neither of which were available at the time. But two groups have now realized Gabor's dream. In the 7 March issue of *Nature*, Miklos Tegze and Gyula Faigel of the Research Institute for Solid-State Physics in Budapest announced that by using atoms within a specimen itself as sources of coherent x-rays, they had made the first hologram of atoms inside a solid—a crystal of the mineral perovskite. And in the 22 April *Physical Review Letters*, a collaboration from U.S. and German laboratories reported achieving atomic-scale holography by an equally clever dodge: using the atoms to detect rather than generate the signals.

The reward of these pioneering efforts, say researchers, is a new window on the microuniverse. For discerning the three-dimensional arrangement of atoms inside solids, investigators now rely mainly on x-ray crystallography, in which x-rays are scattered through a crystal lattice to elicit clues about the positions of the atoms. Holography promises to complement the established technique nicely, says Peter Stephens, a physicist at the State University of New York, Stony Brook. "Crystallography is used to determine the average structure of ordered solids," explains Stephens. "Holography, on the other hand, can give you information about local structures that are not seen by crystallography. It offers a way of focusing on the deviations from average—the special cases that may be buried in an otherwise repeating world."



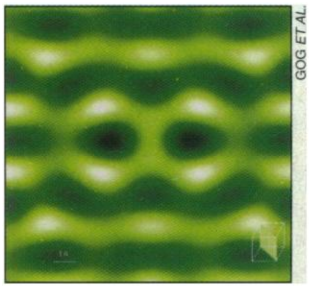
Holography in miniature. Atoms serve as x-ray sources in one version *(top)* and as sensors in another.

X-ray holography might have remained just an intriguing notion had it not been for a suggestion made in 1986 by Lawrence Livermore National Laboratory physicist Abraham Szoke. For holography to work at an atomic level, it requires either the radiation source or the detector to be very near the sample. Szoke saw a way to put the source right inside the sample: by bathing the sample in high-energy radiation, exciting some of its atoms to fluoresce and emit coherent x-rays.

In Szoke's scheme, some of the fluorescent x-rays, the "reference waves," would travel, undisturbed, to an outlying detector. Others, the "object waves," would scatter off neighboring atoms before reaching the detector. By measuring the intensity of the interference patterns created when the reference and object waves interacted, researchers could infer the phase of the object waves and, indirectly, the positions of atoms in the sample. And by tuning the excitation radiation to make specific atoms fluoresce, they could probe particular sample regions. "If you tune it to the minority species, or defects, that's what you'll see," explains Stephens.

Szoke never put his scheme into practice, explaining that it requires extremely laborious measurements of the emerging x-rays. Last year, though, Tegze and Faigel pulled off the feat, known as x-ray fluorescence holography. Exposing a crystal of a perovskite mineral ($SrTiO_3$) to a laboratory x-ray beam, they recorded the longer wavelength x-rays re-emitted by the atoms from 2000 different vantage points above the sample to extract clues to the atomic arrangement.

Meanwhile, the U.S.–German team was proceeding on a parallel track. Their strategy, called Multi-Energy X-ray Holography (MEXH), turns the Tegze and Faigel approach on its head. Developed by Thomas Gog of Oak Ridge National Laboratory; Patrick Len and Charles Fadley of the Lawrence Berkeley National Laboratory and the University of California, Davis; Dietlef Bahr, Gerd Materlik, and Cecilia Sanchez-Hanke from HASYLAB in Germany; and Ralf Menk and Fulvia Arfelli from Brookhaven National Laboratory (BNL), it relies on fluorescent atoms as detectors rather than radiation sources.



First cut. MEXH takes a slice of germanium atoms.

Powerful, coherent x-rays from a synchrotron serve as the reference signal, which travels directly to the fluorescent atoms; synchrotron x-rays scattered off neighboring atoms provide the object signal. Combining at the "detector" atoms, the x-rays excite a fluorescence that varies when the sample is rotated and the interference pattern seen by the atoms shifts. By mathematically interpreting changes in the fluorescence, researchers can pin down the positions of the scattering atoms.

After preliminary measurements at HASYLAB, the team tested the approach last summer at the National Synchrotron Light Source at BNL. In separate experiments, they recorded holograms from crystals of the mineral hematite (Fe_2O_3) and germanium. Although the measurements were just as laborious as those required for the earlier technique, Gog says MEXH has a key advantage. Because the x-rays that probe atomic structure come from a synchrotron source, the researchers can tune them, making measurements at multiple energies. And that can eliminate the aberrations—twin images or image cancellations—often seen in holograms created at just a single energy. Szoke, however, believes it's too early to say which approach will win out.

Although x-ray holography, like crystallography, cannot illuminate highly disordered samples such as living biological tissue, it could be a boon to materials scientists. "One of the things that holography may do well is to look at the structure of very dilute things in materials," says Fadley. Besides impurities, these promising targets include defects in semiconductors and so-called "buried interfaces"—places where separate sheets of crystalline material join together.

Within a month or so, Gog, Fadley, and their colleagues plan to test that potential by making holographic snapshots of tiny lumps of germanium—no more than 10 to 20 atoms—embedded in a silicon lattice and single layers of germanium atoms sandwiched between layers of silicon. "This is the first time holography is being tried on something where we don't know the answer in advance," Gog says. "That, of course, is the whole point."

–Steve Nadis

Steve Nadis is a writer in Cambridge, Massachusetts.