Disorderly Light

Solid-state physics offers new insights to classical optics

By IVARS PETERSON

Laser light reflected from a sheet of white paper looks strangely mottled. Instead of a smooth distribution of light, one sees a speckled spot.

This well-known optical phenomenon hardly seems related to the passage of electrons through a wire. But researchers who study optical effects are now turning to solid-state physics for fresh ideas, and in doing so they have found that recent theories about electrical conductivity in microscopic wires provide surprising new information about laser speckle patterns.

The mathematics of waves provides the link between the seemingly unconnected fields. Over the last 10 years, solid-state researchers have discovered that electrons display a number of unexpected properties when driven through microscopic samples of disordered solids chilled to temperatures below 1 kelvin. To explain these observations, they assume that the electrons are behaving more like waves than particles. Theorists have found that by using quantum mechanics they can explain most of the observed effects in terms of wave interference—the reinforcing or canceling effects caused by overlapping waves.

Theorists' success in using wave ideas to describe and predict novel phenomena in disordered solids has prompted a search for equivalent effects in other fields where wave equations play central roles — including acoustics, magnetism and plasma physics, as well as optics. Insights gleaned from solid-state physics also suggest the possibility of a new type of imaging that researchers could use to investigate what is happening inside murky liquids and to determine the strength of metal samples crisscrossed with microscopic cracks.

"We are beginning to realize that all the new discoveries and advances being made while studying disordered solids will be relevant for all these other fields," says physicist Ad Lagendijk of the University of Amsterdam in the Netherlands. "Optics is the first domain where [these] solid-state predictions are being tested."

The new connections between solid-state, or condensed-matter, physics and other fields were the focus of several papers presented at last month's American Physical Society meeting in Cincinnati. Physicists Shechao Feng of the University of California, Los Angeles, and Patrick A. Lee of the Massachusetts Institute of Technology review the link between electronics and optics in the Feb. 8 SCIENCE.

An electron making its way down a metal wire faces numerous obstacles. Impurities, other electrons, crystal-grain boundaries, crystal defects and the collective vibrations of the wire's metal atoms all hinder its passage.

The progress an electron makes — hence, the material's electrical conductivity — depends on the wire's composition, temperature and size. In a metal wire less than 1 micron thick and cooled to a temperature below 1 kelvin, an electron behaves much like a laser beam, acting as a coherent wave propagating from one end of the wire to the other.

"In this quantum regime, you have to think of the electron as a wave rather than as a particle," Feng says. "You have to go all the way to the Schrödinger equation [of quantum mechanics] and the wave description of electron propagation."

In the last few years, solid-state physicists have become particularly interested in the properties of disordered solids and the effect of this disorder on characteristics such as electrical conductivity. They have found, for instance, that a jumble of foreign atoms randomly distributed among a wire's metal atoms scatters an electron wave, frequently changing its direction in much the same way as tiny globules in milk scatter light to give the liquid its characteristic white color and opaque appearance (SN: 3/23/91, p.182).

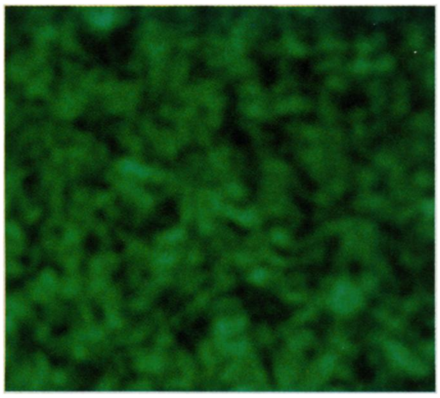
When impurities are present, electron waves propagating down narrow wires scatter not just once but hundreds or thousands of times before they emerge. Researchers have discovered that despite these random interactions, the multiply scattered electron waves still combine to create distinctive interference patterns.

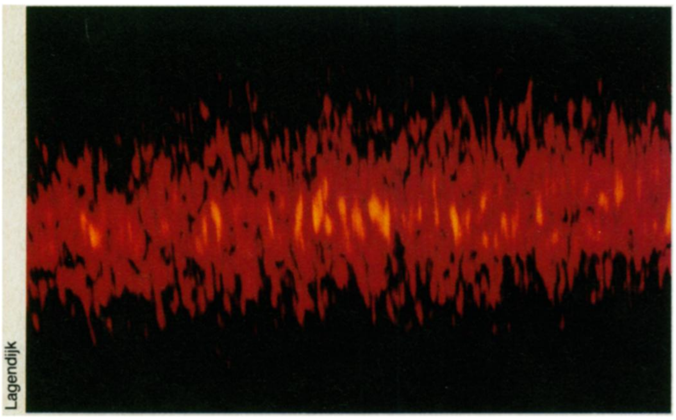
"The lesson of solid-state physics is that it is quite possible to generate circumstances where these scattered waves do interfere," Lagendijk says.

This interference effect manifests itself as variations in a quantum wire's conductance—a measure of its ability to conduct electricity. Theory predicts that wires of the same dimension and composition would show slightly different conductances, reflecting differences in the positions of the impurity atoms responsible for scattering the electron waves in each sample.

Experimenters can duplicate the effect by varying the magnetic field applied to a single wire — a change equivalent to randomly shifting the positions of the impurity atoms. As the magnetic field increases, the wire's conductance fluctuates up and down. Researchers would have observed no such fluctuations if the scattered electron waves had not generated characteristic interference patterns.

These experiments and the accompanying theoretical work in solid-state physics demonstrate that, contrary to long-held assumptions, multiple scattering doesn't completely wash out the information carried by waves. Investigators can now use the resulting interference effects to obtain valuable information about any medium in which





Lagendijk

Speckle patterns created by green laser light reflected off a dry coat of white paint (top) and red laser light scattered by a bundle of randomly positioned, closely packed optical fibers (bottom).

waves are multiply scattered.

"Multiple scattering doesn't have to be bad," Feng says. "It can actually tell you quite a lot."

This insight applies not only to electrons in a quantum wire but also to a laser beam passing through a translucent glass slab. Tiny air bubbles distributed throughout the glass scatter the laser light in all directions, producing a kind of interference pattern – consisting of an apparently random distribution of bright and dark speckles – where the beam emerges.

"People thought of a speckle pattern as a random pattern," Feng says. Physicists assumed that any change in the laser beam's direction or frequency would create a new speckle pattern completely unrelated to the original pattern.

But experience from solid-state physics suggested otherwise to Feng and his collaborators. In 1988, they predicted that a small shift in the angle at which a laser beam enters a multiply scattering medium such as a translucent glass block would also shift the speckle pattern – without significantly altering its basic structure. Researchers in Israel subsequently observed this so-called "memory" effect in laser light transmitted through a thin sheet of opal glass.

"When you change the incoming laser beam a little bit, you get a new speckle pattern, which again looks random," Feng says. "But when you look more closely, you see that the [old and new] patterns are really very similar to each other." The basic pattern simply shifts in position.

The same idea applies to the speckle pattern created by laser light bouncing from a microscopically rough surface, such as a sheet of white paper or a wall coated with white paint. "This is quite amazing," Feng says. "A speckle pattern is in fact not random."

"The condensed-matter theoreticians have taught the optical people a lesson," Lagendijk says. "The study of speckles turns out to be a very fruitful way of investigating the propagation of light."

Indeed, just by observing shifts in speckle patterns, researchers can actually detect changes in the direction of an incoming laser beam. Feng likens the process to watching someone behind a sheet of smoked glass: Although you can't tell who it is, you can easily tell how much and in which direction the person moves.

Such motion-detecting capability may prove useful for studying phenomena as diverse as the propagation of radar waves through clouds, sound waves through solid materials, and light waves through colloids such as milk.

Feng is now exploring the theoretical possibility of using laser light to image a stationary object immersed in a milky fluid. His initial, unpublished analysis shows that such imaging may be feasible, he says, "but we're still not there."

Ultimately, medical professionals might even be able to use laser light to peer through skin and other tissues. "One of these days, our new understanding that it is possible to make images even in diffuse [multiply scattered] light might make it possible to image tissue and cells inside the human body," Feng muses.

Optics researchers now have a chance to repay their debt to solid-state physics. It's often easier to do interference experiments with light than under the extreme conditions required for electron wave studies. By taking a closer look at interference effects in light, these investigators may uncover new phenomena of interest to solid-state physicists.

Other scientists may also reap the benefits of this research. Multiple scattering plays important roles in fields ranging from particle and nuclear physics to atomic and molecular physics.

"Many new interference phenomena in multiple scattering are being found in many different fields," Lagendijk says. "They can all be explained within one theoretical framework. This is a real case of the unification of knowledge ... in science." ☐