To Discover a Dream Material

We watch electrons—a billion times smaller than atoms—in complicated materials to enable the unimaginable materials of the future.

Seeing Electron Waves
To see miniscule subatomic quantum-mechanical waves shooting around in a piece of material is beautiful. It’s like looking at Cayuga Lake on a breezy, blustery day: you see waves of large amplitude, lots of short waves, and long waves all interfering with each other, making a very complicated visual pattern. That’s what I see—the same kind of wave patterns, but now quantum mechanically—when I watch electrons in materials. I had to invent a scheme to be able to see this.

To develop the unimaginable materials of the future, we need to see how electrons move in complicated materials.

Complicated 21st-Century Materials
We have known for 50 or 60 years how to design instruments and materials, like silicon, gold, aluminum, and platinum, for use in our technology. But the new electronic materials being developed in the 21st century are immensely more complicated than a familiar material like silicon or gold.

It has been extremely challenging to understand the properties of new materials—how and why they work. One of the reasons is because scientists could not see directly what electrons are doing in these materials. But as soon as we developed a technique to visualize the action of the electrons, we saw that it’s extremely complicated. My lab develops tools, approaches, and instrumentation to tackle the complications—to visualize what’s called complex electronic structure, which describes how the electrons work in complicated 21st-century materials.

From Seeing Atoms to Seeing Electrons
The technique my lab developed is called spectroscopic imaging scanning tunneling microscopy. It works like an atomic-scale gramophone.

If you think back to the way an old phonograph LP works, a needle moves
around on the surface—it’s a moving plastic disk with wiggles on the grooves, and a stationary needle conforming to the wiggles. This mechanical motion sends a signal to the audio amplifier, which sends a signal to your ear.

Now shrink that apparatus down by a factor of a million. The tip of the needle is one atom, and the surface has a small number of atoms in it. You move the needle around and measure electrons jumping from the needle to the surface. By measuring this electrical current, we can take an image of where the atoms are.

This apparatus, invented in the mid-1980s by two Nobel Prize–winning physicists, is called a scanning tunneling microscope, an STM—the first device for seeing atoms. It’s a fabulous device, but we can’t see electrons with it.

My challenge was to go beyond that state of the art to a new level, where instead of seeing the atoms, we could see the electron waves. I took the same approach of atomically sharp needles scanned over a surface, but I measured a different physical property, which concerns electrons and not atoms. We created an instrument that lets us see electron waves as they zoom through crystals. It was difficult! It took about 15 years and about 100 man-years to develop the instrument to its present capabilities.

The Search for New Super Materials
In your home, you have ferromagnets—refrigerator magnets—a quantum-mechanical material. It’s magnetic because the electrons zoom around in circles and never stop. The magnetism does not decay. It survives forever. Other possible quantum-mechanical materials may exist, which we could use in our technologies. But we’re searching for them. We know they can exist theoretically, but we have not developed them to the point where we can use them in our phones and iPads.

One of them is called a superconductor. It’s a material through which electrical power can pass without any dissipation. Your laptop would never get hot if it’s a superconducting laptop, because it would not use any energy. It would also work a thousand times faster. Superconductors need very low temperatures before they can work.

We need room-temperature superconductors,
Why this Research?

The fundamental issues in this field are some of the most profound in physics. Although we talk in terms of making new materials, iPads, saving energy, and so on, for a physicist, there are deeply profound questions posed by the existence of complex materials. It's fascinating as a professional to have an opportunity to learn about and attempt to solve some of these problems. I want to mine down and get to the lowest, most elementary, most elegant level of explanation of what's going on. I've had marvelous opportunities and very good luck. I also have wonderful colleagues at Cornell with whom to collaborate in this area of research. I'm delighted to have a career as a physicist. I wouldn't change it for anything.
but we do not yet know how to develop them. For the ones we know about, we have not figured out why they are so complicated.

**Figuring Out the Complication**

One of the things we discovered here at Cornell in the last few years about the complication of new materials is this: when we look at them directly at the atomic scale, electrons are not simply moving around through a piece of silicon. They are in a complex, self-arranged relationship in the material.

Neither the theory nor the experiment exists to discover or develop new materials under these circumstances. Fundamental-level work has to be done first to understand the basics. My lab is trying to figure out how the electrons cooperate together, so that they can travel through a material with no loss of energy. We hope this knowledge will help lead to the discovery of room-temperature superconductors.

**What’s Super about Room-Temperature Superconductors?**

We have longed dreamed of having superconducting computers. With room-temperature superconductors, you would not have to recharge your iPad battery, and its efficiency would be much better. Now, think about Google’s server farms, where each server farm with millions of computers is bigger than a football field.

These server farms have one of the most rapidly increasing rates of energy usage of anything in the world, because every classical computer uses lots and lots of energy. Superconducting computers would not use this energy. Instead of using megawatts to run a server farm, we could use a kilowatt and get far more computing power.

Another example is the new photovoltaic solar cell arrays, which will be built in southern California, Arizona, New Mexico, and other places. Power needed in New York City is generated in the desert. We cannot build a high-voltage power line across the whole country from every wind farm and photovoltaic installation, generating gigawatts of power from sunlight. We would need an efficient and unobtrusive new way to send power from remote and ecologically appropriate power generation sites to where the power is needed—East and West Coast cities.

One way to do this would be to use superconducting power transmission. We could send enormously more power through a nondissipative superconducting cable than through a regular copper wire—and at zero voltage. With cheap room-temperature superconductors, we could revolutionize power generation and transmission. It would change the world.