Title

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Journal

Berkeley Scientific Journal, 27(2)

ISSN

1097-0967

Authors

Sanghal, Tanya
Sabharwal, Baani
Delaney, Andrew

Publication Date

2023

DOI

10.5070/BS327262055

Undergraduate

Superconductors and Spintronics: The Future of Hyper-Efficient Data Storage and Transport

INTERVIEW WITH PROFESSOR JAMES ANALYTIS

BY Tanya Sanghal, Baani Sabharwal, and Andrew Delaney

INTERVIEWS

Dr. James Analytis, *is the Physics Department Chair at the University of California, Berkeley. After receiving his Bachelors in Science from Canterbury University, Dr. Analytis completed his doctorate at the University of Oxford while working with Stephen Blundell and Arzhang Ardavan on experimental and computational studies of quasi-two-dimensional organic superconductors. Following his graduate studies, Analytis continued his work on superconductors at the University of Bristol and later at Stanford University. As an experimentalist lab in condensed matter and material physics, the Analytis lab focuses on creating new materials that have technological applications related to superconductors, exotic magnets, and topological insulators. They also focus on understanding these materials' novel quantum behaviors and physical properties.*

BSJ: We understand that you are the Department Chair of Physics, and your research concentrates on condensed matter. How did you become interested in this particular field of science?

JA: I think for a lot of us, when making critical decisions about what direction we pursue, it is a complete accident. When I was doing my undergraduate degree in New Zealand, I was interested in a lot of different areas of the physical sciences. My physics mentors greatly shaped my interests—I had a professor who was doing interesting research, and I liked the lab culture. So, I joined the group for a summer and ended up doing an honors project, often referred to as a research thesis. I realized that condensed matter physics encompasses many different sectors of physics. For example, particle physics might investigate the essence of matter, the fundamental constituents of the universe, teaching us about the different "colors and flavors" of matter, neutrons, neutrinos, and quarks. In that sense, particle physicists understand what matter is made of in the deepest way. Then, there are other aspects of physics concerned with how things respond to different conditions. For example, why does metal feel cold to the touch? Why do different things heat in different ways? Why can you not make a wire out of plastic? The answer to these questions lies in how the aspects of matter learned in particle physics interact with each other. I was really excited about the idea of becoming a condensed matter physicist because you not only need to understand what things are made of but also how those things interact.

These fascinating interactions are what result in different properties in, for example, a magnetic versus a non-magnetic system, a metal versus an insulator, or a superconductor versus a non-superconductor. All of these differences in properties come from the interactions of different particles. For me, the key intellectual leap was the fact that you can understand everything about an electron but know nothing about what happens when it is interacting with all the other particles. Analogously, you can understand everything you want about a single cell but know nothing about the function of an organ. Or, you can know how the intricacies of the brain function but know nothing of how prose and poetry emerge from our biological functions. What led me to condensed matter physics is the desire to understand the complex interactions of sub-atomic particles in order to gain a deeper understanding of physical properties in material science.

BSJ: You have described that your interest in superconductors began at the University of Oxford. Could you expand on why superconductors interest you so much?

JA: Superconductivity is a phenomenon that is fundamentally unknown. There are lots of questions about how object interactions lead to superconductivity. In other words, there are a lot of complex questions that I would call "physics" questions that are really important but unanswerable.

Then, there is the technological aspect of superconductivity. In principle, if we can make room-temperature superconductors, we can suddenly fundamentally change our relationship with energy. In fact, there was a recent announcement—however, very controversial—about a room-temperature superconductor by Chang and Kenneth[1]. A key example of a room-temperature superconductor application that might not be immediately obvious is MRI scanners. MRI scanners actually work because of the superconducting coils inside, which require special facilities to cool. In fact, most MRIs utilize liquid nitrogen or liquid helium vats—an extreme cost. This is why there are very few MRI scanners in developing nations. But if you had a room-temperature superconductor that did not require cooling, you can imagine designing a whole new diagnostic system that is much more portable, efficient, and accessible. That is one of the many notable game-changing applications of a room-temperature superconductor.

BSJ: Can you explain exactly what a superconductor is and the mechanism behind the technology?

JA: The simplest way to explain superconductors is to discuss their properties. First, a superconductor has zero electrical resistance. When you pass current through a wire, it heats up because there is resistance in the wire. This is how the old-style light bulbs used to work: a large enough current passes through the tungsten light bulbs, and they heat up so much that they start to glow. But when transporting energy, resistance becomes a problem—you use a lot of energy traveling from point A to point B. When electrical resistance is zero, you can transport energy infinite distances away without any loss of energy.

The second property of superconductors is that they do not produce magnetic fields. If you apply a magnetic field, a superconductor automatically orientates itself so there is no magnetic field inside the wire, whereas normal copper wires do not do this. One of the reasons why this is useful is because of the way we use MRI scanners and other things like levitating trains—it lets you move long distances frictionlessly.

Now, how do superconductors work? The key part is that there are interactions mediated between electrons. We can see this type of interaction when pushing two hands together. The hands would not melt together; rather, they would push against each other because of Coulombic forces. Essentially, the electrons on our hands are repelling

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[1] *Kenneth Chang, "New Room-Temperature Superconductor Offers Tantalizing Possibilities," (The New York Times, 2023)*

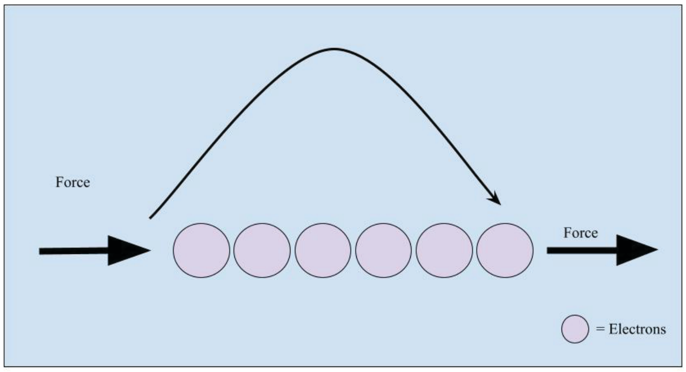

Figure 1: Electricity Transportation Model. This model illustrates how an electron can transport electricity without a loss of energy by relaying its signal to electrons not directly adjacent to itself.

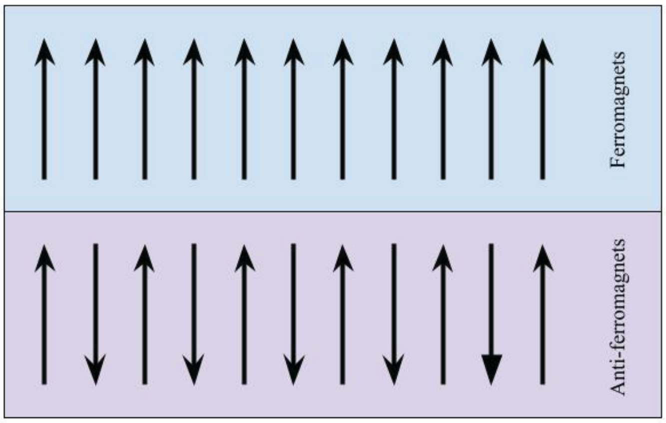

Figure 2: Ferromagnets vs. Anti-Ferromagnets. The above figure illustrates the differing electronic spins of ferromagnets and antiferromagnets. The differing orientation results in an antiferromagnet having no net magnetism.

each other, which is only felt at short distances. Sometimes these interactions are attractive, which means that they want to stick together. Consider sticky tape: you put sticky tape on something, and it does not want to be pulled off because of Van der Waals forces.

It is the same idea with superconductors, but now electrons are being bound by what is known as a fermi arc, a quantized vibration of the solid. All of the atoms are vibrating in the system, and they mediate an interaction between two electrons to form a bound pair together. Why does this lead to zero electrical resistance? This bound pair can be very large distances apart. If you push one, it immediately pushes the other because they are interacting as a single object. This single object can now essentially transport electricity without loss in energy because no single electron travels; this whole object is moving in harmony. It is similar to the way that if I push on one side of a book, you would immediately feel a force on the other side.

BSJ: One of the main focuses of your lab is studying the interactions of electrons' spins and manipulating them to advance superconductor technology. Can you explain what antiferromagnets are?

JA: Most magnetic material falls into one of two categories: ferromagnetic or antiferromagnetic. Recently, we have discovered that there are many in-between states, but in general, it falls as one of the two. Ferromagnets are what are conventionally thought of as magnets—the thing that sticks to your refrigerator. These magnets have a net magnetic moment. When the electrons of the metal on your refrigerator see that magnetic moment, they want to stick to it and form their own dipole. An antiferromagnet is a special kind of magnet that has no net magnetic moment. The electron spins in a ferromagnet are all aligned in one direction, while the electron spins in an antiferromagnet are all anti-aligned—a fancy way of saying that one is up, then down, then up, and so on. The spins alternate throughout the whole material resulting in the average magnetic moment being zero, even though locally the spins are actually ordered and pointing in the same direction, like a ferromagnet.

BSJ: How do antiferromagnets relate to spintronics?

JA: Spintronics, as you might guess, is derived from the word "electronics." Electronics are devices built on the properties of electrons; they use electrons to store and transport information. Spintronics uses spins instead of electrons to do the same things.

When you are moving electrons to transport information in your device, they encounter electrical resistance and get hot. My lab is investigating the possibility of storing and transporting information without actually moving the electrons but instead flipping the spins. It works a little bit like the ferromagnet that sticks to your refrigerators. Recall that, in a ferromagnet, all the spins are aligned. If I alter one spin, all the other spins will follow in a cascade. You can alter these spins by injecting spin currents or applying small magnetic fields locally.

The basic idea of spintronics utilizes this mechanism. If I flip the spins of the electrons in a particular spot, it will transport that spin to the other side. This results in information being transported without any movement of electrons. Because of this, it is the lowest-energy process to transport information.

One problem with this technology is that the antiferromagnet has a little dipole moment. Imagine that I have another ferromagnet with stored information next to it; these things can, unfortunately, affect each other. If I flip one ferromagnet, it might accidentally flip its neighbor. Because of this, they have to be further apart—one of the main challenges of magnetic memory.

BSJ: Can you elaborate on why superconductors require really low temperatures to function? How is your lab manipulating materials in order to achieve room-temperature superconductors?

JA: If you raise the temperature of a metal, it melts—the atoms fall apart from the crystal structure they previously formed. This is because you have reached a temperature higher than the energy of the interactions between the atoms. It is the same with superconductors.

There is an energy scale associated with the interactions between the electrons. If the temperature exceeds the attraction, they will not glue together.

Electrons pair because of vibrations in the solid. The heavier the atom carrying the vibration, the harder it will be to move them and create those vibrations. Therefore, heavy elements generally mean lower superconductor temperatures. The trick in the paper on antiferromagnetic switching[2] was to use really light elements. They have used hydrogen, the lightest element on the periodic table, to make a superconductor. This decreases the mass of the atoms, making it much easier to excite the vibration that sticks the electrons together.

BSJ: What are some current challenges that you face in your research?

JA: When you work in the world of new materials, like condensed matter physics, you cannot apply the same techniques to characterize them since every material is slightly different. For example, one might be slightly more or less air-sensitive than others, so you cannot keep it out on the table for very long. You might be able to make contact with one material really well to measure its resistance, but with other materials, it seems impossible. The technical challenge that our lab has is mostly having versatile enough techniques that would allow us to adapt to new materials. This is very specific to my lab group because we make our own materials, each with their own peculiarities.

Another challenge is getting to very low temperatures. Some of the properties of a material cannot be understood until you remove temperature as a variable. We have to get to very, very low temperatures—a few millikelvins above absolute zero.

A high magnetic field is another challenge. Sometimes you need to apply large magnetic fields to flip those spins to see the measurable changes in energy. For example, when an antiferromagnet is aligned and a single spin is flipped, it tells you what the attraction is that is keeping them in that specific direction. The same is true for a superconductor; magnetic fields break apart electron pairings and tell you the energy scale.

BSJ: Condensed matter physics is often considered a heavily theoretical field. What do you think are the societal implications of your research?

JA: Earlier, I discussed how a room-temperature MRI would greatly increase accessibility to the diagnostic tool; however, my research also has amazing implications for the storage of data. The growth of data centers is only going to become more urgent over the next decade. They are predicting that most of the energy budget is going to be in data centers in the future. If such a huge fraction of the Earth's energy budget is being dedicated to computation, then we are going to have to figure out some way of having lower-power electronics, potentially using spintronics[3,4]. The goal is to create components that use a fraction of the energy that we are currently employing. You can already see the progression of powerful computers and phones, which is pretty revolutionary. It is those kinds of game-changing possibilities that can happen in the near future.

BSJ: What are the monumental questions of condensed matter physics today? Where do you see your research going, and what are your goals for future research?

JA: I have mentioned the mechanism of superconductivity for the class that is understood. But there is a whole other class of superconductors, known as high-temperature superconductors, where it is not understood at all. The mechanism that I previously described is definitely not what is happening. This is a huge question in condensed matter physics today.

We have focused on strange materials on the border of superconductivity and magnetism. We realized that we can manipulate them at much lower energy scales to create memory devices, like the antiferromagnetic spintronics that I discussed previously. In this sense, the applied side of our lab's research is getting more exciting. The other side, which is also exciting, is that our lab has begun to use state-of-the-art nanofabrication materials. Usually, these materials are reserved for the semiconductor industry. However, we are exploring these materials on a microscopic level to attempt to thoroughly understand what is going on. So, our two future lab goals are exploring new applications of these exotic materials and using high-end characterization techniques to get to the microscopics of these materials.

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IMAGE REFERENCES

1. Headshot: [Photograph of James Analytis]. https://vcresearch.berkeley.edu/faculty/james-analytis. Image reprinted with permission.

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