Physics for the 21st Century

Unit 6: Macroscopic Quantum Mechanics

Jenny Hoffman and Deborah Jin

Super efficient power grids…magnetic levitating trains…nuclear magnetic resonance imaging…the Large Hadron Collider

At the heart of all of these technologies are superconductors, materials with zero electrical resistance that can carry current without loss and produce intense magnetic fields.

Superconductors are an example of quantum mechanics operating tangibly, in the everyday world. However, they currently have one major drawback. To work, they require an extremely cold environment. They must be cooled to hundreds of degrees below room temperature. And to achieve these cold superconducting temperatures is costly.

Reliable, affordable room temperature superconductors would create new technologies and could power our future. Physicists are working hard to find ways to raise the critical temperature at which superconductivity kicks in.

But first, they have to understand what's going on inside the materials.

Harvard's Jenny Hoffman is exploring the problem by using a scanning tunneling microscope to unravel the properties of superconductors, atom by atom.

Meanwhile, Deborah Jin, a physicist at the National Institute of Standards and Technology, is looking at the problem from a different angle. She is building models for how superconductors work using simpler systems that can be manipulated at the quantum level.

These researchers are on two separate paths, trying to discover the fundamental mechanism behind high temperature superconductors.

Part I: High Temperature Superconductors

Jenny Hoffman

JENNY HOFFMAN: *I'm just curious about how things work. I think I became a scientist because my mom had been a physics teacher and she brought home cool demos. I saw a laser and I thought that was awesome and you know she'd bring home dry ice and I thought that was amazing that gas could be a solid. And I've always liked* *quantitative puzzles and so it's a way to combine sort of curiosity about things around me with my tendency to be quantitative about things.*

Okay I'm turning up the Helium gas. We're going to flow a little.

Jenny Hoffman is a physicist at Harvard University who is exploring new materials that exhibit superconductivity at or near the highest temperatures yet achieved.

JH*: I have been on the exploratory end of things. I look at a new material and I try to understand what's going on in that new material. And I just poke and I look in all different directions.*

So what I do is I build microscopes and I look at the way electrons behave in interesting materials and in particular what I'm interested in now is superconductors

Hoffman's lab explores superconductors. A superconductor is a material with two essential properties. First, it conducts electricity with no loss of energy or zero resistance.

JH: *And what that means is if you take a typical copper cable and you send electricity through the copper cable there's resistance. Those electrons are traveling and they're, sort of, bumping around and they're bumping into all of the different copper atoms as they travel through that wire. And every time they bump they lose a little bit of energy and that energy comes out in the form of heat and light.*

Whereas, if you have a superconductor and you send electrons in one end they just come out the other end without losing any energy. So in the case of a light bulb, it can be very useful that there's resistance and that some of the energy is being thrown out in a form that's useful to us. Whereas, on the other hand, if you wanted to take electricity from a power plant to your home it's really a pain that about ten percent of the energy is lost in the form of heat in that big copper cable coming between the power plant and your home.

In addition to conducting electricity with zero resistance, superconductors expel magnetic fields. Cooling a superconducting material below its critical temperature will cause a magnet to levitate above it. How the superconducting material expels the magnetic field depends on what type of superconductor it is.

Type I superconductors expel the magnetic field uniformly. Type II superconductors allow the magnetic field to penetrate, in quantized packets

called vortices.

> JH: *Every vortex contains a quantum of magnetic field. And these vortices can move around. These quanta of magnetic field can move around within your superconductor. And when they move, that's bad news. They cause dissipation. So as long as they're standing still, your material still superconducts. It still carries electricity without resistance. But as soon as those vortices start moving, you start having energy loss.*

Both Type I and Type II superconductors must be cooled in order to function. The first superconducting material was discovered in 1911, when mercury, a Type I superconductor, was cooled to four degrees Kelvin. Over the years, scientists uncovered other materials that could superconduct, but only at slightly higher temperatures. After decades of research, theorists concluded that superconductivity above 30 degrees Kelvin was not possible. But in 1986, a breakthrough occurred when a new class of superconductors was found -- high temperature superconductors.

The first high temperature superconductor worked at slightly above the 30 degree Kelvin threshold. Then, scientists made a giant leap forward and discovered many Type II superconductors that functioned at over 90 degrees Kelvin.

> JH: *These so called high temperature superconductors are not at temperatures that the typical citizen would consider high. They're still quite low temperature. These are super conductors that work at about 90 Kelvin. The reason that that is potentially very lucrative is that nitrogen, 80% of our air, liquefies at 77 Kelvin. Nitrogen is abundant, it's cheap, and it's easy to liquefy. So if we can cool materials down to the temperature of liquid nitrogen and they have these extraordinary properties, then we have potentially a very useful technology.*

All known high temperature superconductors are Type II, and therefore have vortices. Hoffman's team is currently studying a new superconducting material in detail, exploring the motility of its vortices and other properties. If they can understand the underlying properties of these high temperature superconductors, they can apply that knowledge to focus the search for new materials that function at even higher temperatures.

> JH: *So the material I'm looking at right now is barium cobalt iron arsenic, which is one of these very new high temperature superconductors discovered in February of 2008 and I'm trying to understand how the electrons interact in that material. So what I'm actually looking at is a few little millimeter fragments of this material, which I put into my low temperature microscope.*

JH: *So I mean one millimeter is the standard sample size.*
NICK LITOMBE: *So as big as possible.*

Professor Hoffman's lab explores this new superconducting material with a scanning tunneling microscope, known as an STM. This powerful technology creates images of these materials at the atomic level.

Tess Williams is a graduate student in Hoffman's lab.

TESS WILLIAMS: *So what we're looking at here is a topographic image that shows atomic resolution. So each of these little individual circular bumps here is an individual atom. I still haven't gotten over thinking it's really cool, that I can go into work every day and take pictures of atoms and I can see individual atoms with this microscope. That's not something I ever expected to be able to do.*

Exploring superconducting materials at the atomic level is no easy task. Hoffman's team must first carefully construct the scanning tunneling microscope from scratch. The entire room is built on springs to stabilize the machine and to isolate it from any outside movement. Then the bottom of the experiment has to be held in an ultra-high vacuum.

And finally, the key assembly is a tiny, delicate instrument that moves a needlelike tip in a precise series of scans, just above the surface of the small millimeter sample.

JENNY HOFFMAN: *The scanning tunneling microscope --really all it's about is bringing a very sharp tip very close to the sample that you're interested in. And when I say very close, I mean angstroms. That's ten to the minus ten, ten to the minus nine meters. And that distance is so small that's it's actually very hard to accomplish that kind of proximity. And so we have a several inch instrument that is just dedicated to approaching that tip close enough to that sample to make that measurement.*

The sharp tip moves incredibly close to the sample -- a distance equivalent to the width of only a few atoms. Then an electric voltage is applied between the tip and the sample. Electrons move through the tip in response to the voltage, and jump across the gap into the sample.

This current of electrons can be measured and the amount of current measured reveals features of the quantum mechanical landscape electrons inhabit just below the tip. Scanning the tip over the entire sample creates a map of what the material looks like from an electron's point of view.

JH: *So what we're doing to make an image with our STM is we're just measuring the current as a function of location. And we just go to one pixel and we measure the current and we go to the next pixel and we measure the current and we go to the next pixel and we measure the current. And then we have a whole bunch of current data points from each of these different pixels and we plot them on a color scale and that's what makes a picture.*

TESS WILLIAMS: The whole reason that people care about superconductors is that you can transmit energy without any loss.
So this is one of the class of materials called Iron-arsenic superconductors, which are a high temperature superconductor. They are also a Type II super conductor. So in this image the areas that are the green and yellow and a little bit red for example in here, this kind of network. Those are areas where the electrons are still superconducting. And in the blue areas here what we can see is electrons that are in the normal state. They're inside a vortex core. So inside of a vortex the electrons are not superconducting.

The atomic resolution images created in the lab reveal the location and properties of the vortices. The images also show if there are pinning sites that can hold these vortices in place. Hoffman's team wants to know whether the vortices are pinned or unpinned. If the vortices are unpinned, they can move, forming a regular pattern in the STM images. The non-superconducting electrons inside these unpinned vortices will cause energy loss.

Pinned vortices, on the other hand, are scattered irregularly throughout the image. Superconducting electrons can flow freely around pinned vortices, making these materials efficient superconductors. When the team examines an image, they are hoping to see vortices that are pinned.

TW: *If you have a type 2 superconductor where there's enough superconducting part of it left that electrons can still move freely through it. If the vortices are pinned and if the vortices are static the electrons scan just kind of go around them. And they can still act like a superconductor and they can still transmit energy without any loss. So we've imaged vortices here and an interesting fact is that the vortices are not in any sort of regular arrangement. They're kind of jammed in there higgledy-piggledy with no regular arrangement.*

Because there's no longer scale order to it we know that the vortices are pinned and so we immediately know that this material has a lot of promise So this is a really exciting first step and there's a lot of things that we still want to find out about this material.

JENNY HOFFMAN: *Well I'm pretty excited by this brand new* *discovery. I mean we're still less than a year after the initial discovery of these Iron-arsenic superconductors and it's fun for me to be in on the beginning of something.*

We've contributed a couple of things, we've done the first map of vortices in these materials and we've measured the size of the vortices. We've also measured a little bit about how the vortices are pinned in this material and what we found is that without doing any engineering this material already does a pretty good job of pinning those vortices. There are probably a dozen scanning tunneling microscope labs in the world who have tried this material. However, it's hard. The success rate is low. And most labs have given up. I think there aren't too many labs who are still pursuing this as hard as we are right now. In order to understand these materials, we're going to need hundreds of different experiments. And I don't think any one experimenter is going to solve the puzzle. I think it's a collaboration between many different types of experiments. I think room temperature superconductivity is going to happen but I think it's at least a decade out. I think it's cool to be on the beginning of something.

No one yet knows exactly how high temperature superconductors work or whether room temperature superconductors are even possible. While researchers like Jenny Hoffman continue to explore the properties of newly discovered materials, others hope to uncover the fundamental physics behind superconductivity.

Physicist Debbie Jin examines ultra-cold gases, a fascinating form of quantum mechanical matter, which if understood, may also shed light on superconductivity.

Part II: Ultra-cold Gases – Superconductor Model

Debbie Jin

Debbie Jin is a physicist at the National Institute of Standards and Technology, located on the University of Colorado campus at Boulder.

DEBBIE JIN: *I study behavior of things that are very, very cold. What happens is you go to the extremes of temperature, and we take things down to those low temperatures. We see new behaviors. In particular, we see quantum mechanical behaviors. Turns out it's extremely relevant to our modern technology which is ultimately based on quantum mechanics, electrons, electricity, etc.*

Could you guess which of those three states you're in and which way is higher energy?

By studying the atoms of ultra-cold gases, Jin and her research group investigate how these atoms can combine to form new and exotic quantum-mechanical states of matter.

Surprisingly, these atoms in Jin's gases have many properties in common with the electrons in superconducting solids. One important similarity is that they are both what physicists classify as fermions.

DJ: *So in quantum mechanics, we can classify all particles based on how they behave quantum-mechanically. And there are basically only two behaviors that have been observed in the universe, and they are associated with two classifications of particles. Those are called bosons and fermions. A boson, the quantum mechanical behavior is that bosons somehow like to do the same thing. And for fermions, the quantum mechanical behavior is they never do the same thing.*

This idea was first formulated by physicist Wolfgang Pauli in 1925 and is called the Pauli exclusion principle. In a trap, atoms can only exist in defined quantum energy levels. The Pauli principle states that no two identical fermions can occupy the same quantum state at the same time. But bosons can. The Pauli principle does not apply to bosons.

At high temperatures, the atoms move freely between levels in the trap. But when a gas of bosons is cooled to an extremely low temperature, something very unusual happens. As the temperature gets colder, the motion of the atoms slows and they occupy lower and lower energy levels in the trap. Finally, when they reach a critical temperature, all of the atoms are in the lowest possible energy state. At this point, the bosons no longer behave as individuals, but act as one, and create a new state of matter, a Bose-Einstein condensate, or BEC.

DJ: *In the condensate, it's a sudden change. So, you lower the temperature of this gas. You go colder and colder -- all you get is a cold gas. And then you hit the magic temperature -- phase transition temperature – and suddenly, you get this condensate, which is as different from the original cold gas you had as a laser is from regular light.*

When a gas of fermions is cooled to the same temperature, there is no phase transition to a condensate, since the fermions cannot occupy the same quantum energy level.

DJ: *And so, at these low temperatures, the motion of the atoms in* *some kind of container --some trap is quantized. And so, there's one atom moving in the lowest quantum mechanical motion state of the trap. And then there's one moving in the second lowest and one in the third. And so, you always have quite a bit of motion or kinetic energy in that gas even at low temperature. But it's not a phase transition.*

So this is the side project…

The Pauli principle prevents fermions from naturally forming a BEC because they cannot occupy the same quantum state. Undeterred, Jin's team and their competitors pushed forward with the idea of creating a condensate out of fermions. They call it a Fermi condensate or degenerate Fermi gas.

DJ: *Seeing the Fermi condensate, that was a completely open question, whether that would ever be possible. And not only was it an open question whether it would be possible -- but there were a number of reasons why you might guess it would not be possible.*

Although seemingly unattainable, Jin and her team set out to create a Fermi condensate. They worked with Potassium-40 atoms, an isotope of potassium.

The team first cooled and trapped the atoms using an intricate combination of lasers and magnetic fields. But this was still not enough to create a Fermi condensate. The trick to producing a condensate out of fermions was to make the fermions act like bosons.

DJ: *So there's this interesting behavior in quantum mechanics, which is if you take two fermions and put them together that particle would be a boson. And its behavior, for example, how it moves in the condensate, follows the behavior of bosons.*

To cause the fermionic atoms to pair up and form bosons, the team strengthened the level of attraction between them by applying an additional magnetic field. And in 2003, Jin and her team achieved what had seemed impossible. They created a Fermi condensate.

DJ: *So for the Fermi gas, if we just cool the atoms down, we would see no phase transition, unless our atoms happen to have a very strong attraction to each other and would form pairs. Well, that's not the case for our potassium atoms. But we can make it the case. The way we make it the case is that we tune an external magnetic field. Tune how the atoms feel about each other, whether they're attracted to each other, or whether they're effectively repelled from each other, and how strongly they're attracted to each other. Now with that strong attraction, we lower the temperature. We can see this phase transition to the Fermi condensate.*

JOHN GAEBLER: *And if they were paired, the images might to your eye look almost exactly the same as they do there.*

In order to gather data about the condensate, the team takes a snapshot of the atoms once they are released from the trap.

JG: *The atoms were held up in the trap, which is somewhere up here. And then they fall, and they also expand. So, you can imagine almost a little cone coming out from a point up here where the atoms started. And then right at this instant, 10 milliseconds after we dropped 'em from the trap, we took a picture by shining the laser beam through. And then, the result is you see the shadow in the beam where the atoms were. And then you can take another picture with the laser beam a few milliseconds later and compare, and when you see the shadow here and not there, by subtracting the two images, you can see the information on the density of the atoms there. And that's what's shown here basically. It's the inverse of this image, so that you can actually see what the atom cloud looked like at that moment.*

Color can be added to the image to help discern more detail within the atom cloud.

DEBBIE JIN: *How's the data analysis coming?*

Much of the important data comes from the edge of the atom cloud. This is where most of the pairing occurs.

In Jin's achievement of a Fermi condensate, the key breakthrough was coercing individual fermionic atoms to pair together creating bosonic molecules. This pairing allowed the team to create a Bose-Einstein condensate out of paired fermions.

The electrons in superconductors also pair up to create a superconducting state.

But unlike Jin's initial Fermi condensate, where the atoms are strongly bound together as molecules, there is a different kind of pairing involved with superconductors called Cooper pairing.

DJ: *We all know two electrons can't form a bound state. There's no like molecule of two electrons. And so, it's an extremely loose pairing -- often referred to as like a correlation in pairing -- you can't think of in real space -- it's just that one electron moving in one direction, and one electron moving in the opposite direction somehow move in some correlated way. And that's the Cooper pairing that causes the superconductivity.*

This explanation of superconductivity was first proposed by physicists Bardeen, Cooper and Schrieffer in 1957 and is called the BCS Theory. Scientists predicted that this theory applied not just to electrons in superconductors, but also to the fermionic atoms in Jin's gases.

A year after Jin coaxed fermions into a condensate of tightly bound BEC molecules, she and her group create another Fermi condensate. This time, using the Cooper pairs of BCS theory. Jin's new condensate is analogous to a superconductor.

> DJ: *Why do we study the Fermi condensate? It's that it's a very nice model system. So, it's a very simple system where we can try to understand the very basic things.*

Today, Jin and her team are exploring an uncharted area of physics -- the crossover region between Bose-Einstein condensation and BCS theory.

> DJ: *The idea is really getting at what's the ultimate connection between Bose-Einstein condensation physics and BCS physics -- that is the theory of superconductivity. The power of our being able to tune the interactions is that we can go toward the BEC limit and toward the BCS limit. But in between as I make the attraction go from extremely weak to extremely strong is in some sense new physics. It's something in between, and that's called the crossover. And so, we're really trying to understand in experiments now how you go from one behavior to the other.*

Understanding this model system in atomic gases may help theorists create better models for high temperature superconductors. In particular, Jin's research sheds light on how hard it is to break apart Cooper pairs in the Fermi gas. The stronger the attraction between pairs, the greater the resistance of the pairs to breaking apart, and the higher temperatures they can withstand.

> DJ: *If you look at all examples that we have of superconductors, different temperatures and whatever, you have no example that tells you actually that room temperature superconductivity is possible. This Fermi condensate with atoms in a very different system but somehow the same underlying physics says it is possible. It doesn't tell you how to do it in a system that has electrons that are charged. But it tells you that same physics, this pairing of fermions, can happen at a high temperature compared to the temperature scale where quantum mechanics becomes important in the system. So, I think it gives you hope that room temperature superconductivity is possible.*

Debbie Jin examines the pairing mechanism in atomic gases as a model for the pairing of electrons in high temperature superconductors, while Jenny Hoffman explores the properties of the materials themselves. These two distinct lines of research may ultimately merge into a better theory of superconductivity. Someday, it may be possible to engineer atomic structures that create superconductors at ever higher temperatures, reaping new benefits for society.