Episode 18: That Superconductor Episode
Physicists: Fiona Burnell, Darren Peets

Transcribed by Denny Henke

Ben: Over the course of my studies in theoretical physics I've traveled across the continent and around the world sampling new ideas and tasting different answers to the questions of how and why. And still I find there remains a deep hunger which lives within me, a burning desire to share these great ideas with the people around me. And so, I have assembled a team of some of the greatest, most lucid, most creative minds, I have encountered in my travels and I call them my Titanium Physicists. You're listening to the Titanium Physicists Podcast and I'm Ben Tippett. And now allez physique!

[1:49]

Today we're going to be talking about superconductors. So, to introduce superconductors I thought I'd tell you about regular conductors. So, remember back in high school science class when you were learning about electric circuits? There were three fundamental numbers: the current, the voltage and the resistance. So, close your eyes and remember back. You were sitting at the crappy science desk with the 5 volt battery. That battery is the thing that provides the voltage. And then you had the elements of your circuit: there were light bulbs and wires and resistors all hooked together. And all together the circuit will have an overall resistance that when you plug your battery into the circuit the battery would cause electrons to flow through the circuit. Now, this flow of electrons, the quantity of electrons passing through if you will is called the current. Okay, now, remember, these three numbers: the current, the voltage and the resistance were related using a formula called ohm's law. Now, the rule goes that the higher the voltage is the higher the current will be. But, the higher the resistance is the lower the current will be. Okay, now, open your eyes. I know that this was the first and last physics that many of my high school friends learned. It's kind of a confusing business. So, they decided to spend their lives learning other things. But, that's okay, as it turns out it's not so hard to think about because it turns out that you can think of these different elements of a circuit in terms of a river of flowing water. Now, the quantity of water passing you by at any time is the current and the difference in height between the start and the end of the river is the voltage. So, it causes the water to flow from the left to the right. Now, the crap that the water has to pass through, the reeds, the trees, the rocks and stuff, that stuff slows the water down and that's the resistance. So, a lot of water can flow quickly down a really steep hill driving a current up. But if you throw a lot of crap in the river you can slow down how fast it flows. So, it turns out that in both electric circuits and rivers there's almost always going to be some resistance. So some parts of rivers, like Niagra Falls, say, have a relay low resistance. The water doesn't have much to slow it down as it goes from the top of the water fall to the bottom. And some metals like gold have a really low resistance so electrons can flow through them without slowing down much. So physicists in the early 20th century decided to find out how the resistance of some metal changes as you change their temperature. Generally speaking the lower a temperature you go to the lower the resistance in the metal will be and the faster the electrons will be able to pass through it. They found that if you cool some metals down to really, really cold temperature their resistance suddenly goes to zero. If a material has resistance of zero we call it a superconductor. Now let me tell you, superconductors have crazy properties because all of the electrons moving through them don't ever slow down. If you take a ring of superconducting material for example and you set the electrons circling around the ring because they aren't slowed down by anything you can come back years later and the electrons will still be circling around the ring. What's more, they act really weirdly around magnets. If you try to put a magnet on top of a superconductor the magnet will levitate. It will hover in the air. I mean, I'm sure you've heard of maglev trains right? Anyway, I'm really excited. So, today our guest is Mr. Ryan North. The professional web comic artist, writer and duke of the Internet. He writes dinosaur comics at quantz.com and it's been about ten episodes since he was last here on the show. And since then he's been busy. For one thing he's been writing the fantastic Adventure Time comic book series. I've been reading them regularly and it's even better than the tv show maybe. Also, it's just been announced that the second volume of the Machine of Death short stories has been picked up by Grand Central Publishing House and that it will be released next July. It will be titled Machine of Death Part Deux, This is How You Die. Fantastic. Hello Mr. Ryan North, welcome back to the show.

Ryan: Thank you very much for having me.

Ben: Oh, I'm so excited. Your Adventure Time work is so fantastic. Okay, so, Ryan, for you today I have assembled two of my favorite Titanium Physicists. They are quite clever. Arise Dr. Fiona Burnell!

Fiona: Boink.

Ben: Sweet. Dr. Fiona got her undergraduate at UBC and a PhD at Princeton. She's currently a condensed matter theorist at Oxford University. Now arise Dr. Darren Peets! Dr. Darren got his masters and PhD from UBC where he spent a great deal of time trying to get a fire hydrant elected to public office. He's currently a postdoc at the Max Planck Institute for solid state research where he studies weird magnetic materials.

So, Ryan, do you know anything about superconductors just off the bat?

Ryan: Yeah, I mean, it's my understanding that if you combine with magnets and a theoretical particle accelerator you can travel through time. That's where I'm coming from. That's my basis.

[6:53]

Ben: Okay. Well, the government won't let us talk about the time travel applications. Ever since you know that thing got changed. But, why don't we start by talking about the different fun applications because we're kind of on the forefront of a whole bunch of different uses for these crazy things.

Darren: There's a number of applications for superconductors. Probably the one that you are most familiar with would be maglev trains. Magnets and superconductors don't like each other so you can float a train over a track, that reduces the air resistance or the friction involved and the train can go much, much faster. Another use is you can make lossless power transmission lines although the catch is you have to keep them cold.

Ryan: Yeah, that's sort of where I was coming from with the train. I thought that maglev trains just like, regular magnets with a lot of power behind them.

Darren: So, there's a test track in Japan for instance which is definitely maglev. It involves superconductors for sure. The part in the train as niobium cooled with liquid helium and they've got a project in the works to build a track from Tokyo to Nagoya with an extension planned to Osaka.

Ryan: But if you've got this train that's being powered by the superconductor on the train that needs to stay cold and you know, if the air conditioner breaks or something, does that mean that the train crashes really quick? Because you mentioned that this has properties that when it gets cold sort of, it can warm up really quick, there's not much gradient between non-superconductor and superconductor.

Darren: Right.

Ryan: And how much time do you have on the speeding train.

Darren: Enough time to put a wheel down.

Ryan: So they have, like, emergency back-up wheels?

Darren: They have emergency back-up wheels that can come out of the bottom of the train and for emergency braking in case of an earth quake for instance, they have flaps that can go out on the side for increased air resistance.

Ryan: Like a plane.

Darren: Like a plane trying to stop when it lands.

Ryan: Yeah. I mean, they're not going to ramp over the earthquake.

Ben: How fast can maglev trains go?

Darren: The Japanese test track, the normal operating speed is 500 km/hour. I can't remember what they've tested it to, it's over 550. And they've tested it with trains going in different directions at that speed on the two tracks so they don't knock each other off.

Ben: Alright. What other applications are there? MRI magnets right? How does that work.

Darren: An MRI you need a very high magnetic field and it needs to be uniform and you need a huge amount of current to do that. Particularly over such a large area that you can stick a human inside. So, the magnet is made out of superconducting wire. As long as you keep it cold the current just keeps going in a big loop. Your magnetic field is very, very stable. All you have to do is just keep the thing cold.

Ryan: My wife recently had an MRI scan and they made her sign a waiver that basically said that 1 in 100,000 people will die during a scan.

Ben: Whoa.

Fiona: That's probably unrelated.

Laughter.

Darren: The worst thing that I've heard of happening is, so, if you have something like an iron filing that's managed to get into your body somewhere near the surface and you go up to really really strong magnet, it will have a tendency to try to go flying out and I understand that there was a case where somebody had a filing behind his eye.

Ryan: Oh no. Oh no.

Darren: Other than that they're pretty safe.

Fiona: Unless you wear a pacemaker.

Darren: If you have electronics inside you that are keeping you alive you might want to be a little careful as a precaution if nothing else.

Fiona: On the subject of magnets and superconductivity what Ryan's question about the train crash made me think of, this sort of superconductors are the main way that people make very powerful magnets and some people watching the show may have heard of the accident that happened at the LCH in 2008. So when they were building this big particle collider and basically one of the junctions to the magnets heated up too much so that basically there was the one small spot where the superconductor becomes normal and then suddenly, as soon as it becomes normal the amount of current going through it makes it very, very hot causing the whole magnet to shut down very quickly. And so they basically had a whole bunch of these superconducting magnets, suddenly, it's called a quench when they sort of blow out releasing a massive amount of heat and doing a tremendous amounts of damage to the experiments. So this kind of crash, if you like, in a superconducting magnet, does happen.

Ryan: And we don't know any way to do them at room temperature, right.

Darren: Only in the Terminator movies. Some key component of the Terminator was a room temperature superconductor. Part of the chip as I recall. Other than that the highest temperature superconductor out there is 138° Kelvin at ambient pressure and you can get up into the 160s if you apply pressure to it so we're sort of half way to room temperature.

Ryan: So, a room temperature superconductor, is that just fantasy at this point?

Darren: Well it depends what temperature your room is, really.

[11:40]

Ryan: Let's say 22° Celsius.

Darren: Well, we're not there.

Fiona: I think the honest answer is we don't know. The history of it is sort of interesting so superconductivity was discovered basically a hundred years ago and until the 1980s theorists were convinced that you would never be able to get these things above about 40° Kelvin because there was one mechanism for how this worked that was understood and people had fairly convincing arguments about why that mechanism couldn't get you to particularly high temperature and then it was discovered that there's another mechanism that nobody had thought of which we still don't understand which is the mechanism that drives superconductivity in these very high temperature superconductors. So, first of all we don't understand that mechanism so we don't know how much we can improve those kinds of materials and push their transition temperatures up. But also of course you never know if there isn't some other, you know, mechanism out there that we just haven't discovered yet in principle.

Ryan: Right, well I mean, that sounds pretty credible, I believe you.

Fiona: Hedge, hedge my bets.

Laughter

Fiona: So, the question is how does this actually work at a microscopic level and so we did a show a couple of weeks ago on super fluidity and so we talked about how there are some substances that when you make them very cold they go into what is called a superfluid state where the fluid behaves like it has no viscosity, okay and it can sort of, if you put it in a ring and you start it moving it can just sort of go around forever and a superconductor is very much analogous to this. So, it's like you have a superfluid but of things that carry charge and therefore can carry electric current instead of having a fluid moving with no resistance you can get a current moving with no resistance. And the reason that this was a huge surprise when people discovered it, is that superfluids, physicists knew quite well at that time, had to be made out of something called bosons. Two types of particles that you can have, you can have bosons and you can have fermions. You can never make a superfluid out of fermions for reasons that we don't need to get into and all of the interesting stuff that's happening in metals is really due to the properties of their electrons. So, an electron is a fermion. So how does this work? The basic fact that is important is that if you take two electrons and you sort of stick them together, that this composite object behaves like a boson and so what happens in a superconductor is the electrons basically get stuck together and then these composite objects, these sort of paired electrons go into a superfluid state which is your superconductor.

Ryan: Right. Okay.

Ben: I want you to imagine you've got a chunk of metal and I want you to imagine that you can zoom in on the inside of it.

Ryan: I've read a story about that.

Ben: Alright. So you zoom in and eventually what you see is a lattice of ions, positive ions that are hooked together and a bunch of free ranging elections so it's kind of like the monkey bars at an elementary school. And you have all these electrons floating around through it. So, what causes resistance in normal materials is essentially these electrons as they flow through this system bounce off things. They don't flow in nice straight lines. So, what happens with superconductivity is somehow through this mechanism that we're trying to explain these electrons make it so that they aren't bouncing off anything anymore. They just move straight through.

Ryan: Okay.

Ben: And so, as a result they don't loose any energy to heat, there's no friction, there's nothing slowing them down.

Ryan: So, I mean, this is a minor point, but when you say nothing, are we talking like actual nothing or so small that it is negligible.

Ben: I think that the answer is actual quantum mechanics nothing.

Ryan: Really?

Ben: Yeah.

Ryan: Like this would go infinitely on in a loop if it stays cold.

Ben: Yes.

Darren: If you get a loop of current going in a superconductor, you put a current in the loop, you keep it cold, that current will go on forever.

Fiona: But this has effectively been tested, right. I mean they had a ring that they opened sort of years later and they couldn't measure any change in the current of the ring so certainly it is extremely, extremely robust.

Ben: So, how do you go from electrons bumping into things to electrons not bumping into anything is actually a little bit perverse because you have to invoke quantum mechanics but the outline of this explanation is normal electrons don't like other normal electrons so you can't usually smush two electrons together. And furthermore, electrons are a type of particle we call fermions. That means that they have half integer spin, doesn't matter why they have half integer spin, but this gives them certain properties and one of these properties is that they have to obey the Pauli exclusion principle. So you can't end up with any two electrons that are exactly the same so you can't end up with two electrons that are moving in the same direction and occupy the same point in space.

Darren: So we call these properties quantum numbers. Things like angular momentum, momentum, spin and so on.

[16:45]

Ryan: Okay.

Darren: Every electron in the material must have different properties from every other electron so when you throw electrons into a material it's kind of like filling up a bathtub. They can't occupy the same space.

Ryan: Right.

Darren: The other type of particle, a boson, doesn't behave that way. They're completely happy sharing these numbers and if you cool them down to low temperatures they try to. And you'll end up with all of the bosons in the system, or a very large fraction of them, trying to be in exactly the same quantum state. So that the entire system is one coherent quantum state, acts as one object. It's coherent.

Ryan: Right.

Darren: So, a super conductor is that for charge.

Ben: So, Darren was talking about this bathtub and that's a pretty good analogy. The idea here is that if every particle is unique then when you cooled down the system, they can't all have the same energy. There's a lowest energy and a second lowest energy and a third lowest energy and they kind of stack on top of each other.

Ryan: They can't all have the same energy.

Darren: You can have some that share provided they're, for instance, going in different directions but once you've filled up all of the possible directions they can be moving in because there is a finite number of those thanks to quantum mechanics then you have to go to the next state up.

Ryan: I will accept that is the case. But it sounds crazy.

Ben: So, originally in our metal, you have all these free electrons roaming around and these electrons are fermions and somehow, apparently, there are a few different mechanisms for this but normal electrons repel each other. But somehow, in this lattice...

Fiona: In this material.

Ben: Inside the material these two electrons can be attracted to one another. So, if you cool the temperature down low enough they'll get stuck together. So what happens is instead of a whole bunch of these electrons floating around you have a whole bunch of electron pairs floating around and the big difference between a single electron and two electrons stuck together is that two electrons stuck together have integer spin. I mentioned earlier that electrons on their own have half integer spin, you have 1/2 + 1/2 or 1/2 - 1/2 or whatever you end up with an integer. And the very fact that it has an integer spin as a collective entity, these two electrons stuck together, means that it obeys a fundamentally different type of physical laws at cool temperatures. So, fermions, so electrons alone, do this stacking thing where you can't have any two electrons that are exactly the same but if you stick two of these guys together it becomes a boson and bosons obey something called Bose-Einstein statistics. Anyway the moral of the story is that if you cool it down cool enough all of these different pairs can turn into the same quantum state. So, you can cool them down and they all have the lowest possible energy, they all act exactly the same.

Fiona: Then the actual metal, so you have your whole sort of tub full of electrons. And, basically what happens is that it's the electrons near the surface that pair and so basically close to the surface, they can all fall down to kind of the lowest energy within some window of the surface.

Ben: Right.

Fiona: And so in this way the ones near the surface pair and they sort of fall down a little lower in the bathtub cause it's as if a bunch of the water molecules can sort of sit right on top of each other or something like that and so the surface effectively is lower but it's not that the whole tub is suddenly this puddle at the very bottom if you like.

Ben: The moral of the story is that if we cool down all the electrons inside this metal to a cold enough communal temperature we'll get a whole bunch of these bosons that all have the same quantum number. Anyway, how do we get from having these pairs of electrons to not having any resistivity. How come one of these pairs of electrons can pass through the metal in a way that individual electrons can't?

Fiona: So, the concept we haven't talked about yet, we said, you know, that electrons are sort of glued together in some way. And they make bosons and these bose condense but what we haven't talked about is that these pairs are not pairs of electrons that are sort of taped together so that they sit close to each other. They are pairs of electrons that know exactly that they are moving in exactly opposite speed and direction. So, basically they talk to each other they say okay, I'm going to run as fast as I can this way and you run as fast as you can the opposite way. Then what happens is the electrons are not close to each other and then they have agreed that they are going to run in opposite directions as fast as they can and then one of them runs into a lamp post. Now normally if you were running by yourself and you run into a lamp post you would probably stop but the point is that because of this agreement, that this electron runs into the lamp post but it can't stop without costing a huge amount of energy because it has to break it's agreement with the other electron that they were going to be in this paired state, okay? So, what it ends up doing is actually just jumping over because that is less painful to it than breaking this pairing. I'm sure there's some kind of romantic analogy you could draw there that would be much more entertaining.

[21:44]

Ben: Okay, so it's like this. Imagine that times are really tough, okay. So, like, economically and all these electrons are people. What the people do is they decide to pair up because if you pair up it costs a lot less if you share everything, okay? So, you have these two electrons and they are living together, and the idea is that they are always going to kind of, do the opposite thing so let's talk about energy in terms of like money, okay. To get these two electrons divorced it's going to cost a ton of money, okay. And they are always on the cell phone to one another so as they are wandering on their own through the crystal if one of them decides to spend a whole bunch of money the other will have to earn the same amount of money to compensate. Or, if one spends more than the other earns they'll have to get divorced and that costs a ton of money. So, what happens is as they are traveling through the crystal one of them will say oh, those are a nice pair of shoes I think I'll buy those shoes and phone the other guy and say hey can we afford to buy me a new pair of shoes and the other guy will say, no, I'm not making enough money to buy those shoes otherwise we'll get a divorce so the first electron goes well I guess I won't stop to buy those shoes and just continues on its way. So, as a result you don't have these electrons interacting with anything so in these low temperature systems these two electrons can't afford to interact with anything. How's that for a bad analogy.

Ryan: I read this thing on science reporting and science teaching a couple years back but the person was arguing that analogies and metaphors and explanations are what are killing us because they say things like the electron doesn't like the other electron and you know, you'll have scientists talking like this and it's easy to loose sight of the fact that electrons don't have feelings.

Laughter

Ryan: But having this talk about marriages and divorces being expensive you know, it, I understand it and I mean, I get, on a scientific level that they don't get married but they behave they are and that's sweet.

Ben: The net result then is that all of these electrons can move through your block of metal without encountering any resistance. That's the microscopic story. The macroscopic story itself is kind of fascinating because as we mentioned before you can get magnetic levitation and stuff like that. So, I think we should talk about these interesting macroscopic properties.

Darren: Probably the most famous macroscopic consequence of this is the Meissner effect. If you put one of these super conductors in a magnetic field it tries to expel all that magnetic field. Electrons that are in a magnetic field have to run around in circles. In the case of the super conductor they don't want to do that and they're tied to somebody that doesn't want them to so the whole group of them, everything that is Bose condensed acts collectively to screen all of the magnetic field from the crystal.

Fiona: The important thing in maybe to say is that this flux expulsion is what allows the superconductor to be levitated over the magnet because basically as it goes closer to the magnet there's more magnetic flux and that at a certain point you have to start putting vortices through and those cost a lot of energy.

Darren: The fact that you're running currents in the super conductor to cancel out the magnetic field means that you are turning the superconductor into a magnet with opposite polarity to the one that you've applied. It's like a magnetic mirror. If you bring the superconductor and magnet up to each other it's like you're binging two magnets up to each other but no matter how you orient them they're always opposed.

Ryan: Right.

Ben: So, I've got a fun metaphor for this. Imagine that you've got like a fan, or a couple fans in a room. But you're in a room and you have a fan, I want you to imagine the air circulating as little, kind of, tubes, rings of air that go through the fan and then circulate around back and then go back through the fan again. And there are a whole bunch of these different tubes of air flow. So, the deal with magnets is you can't take two magnets and stick North Pole to North Pole or South Pole to South Pole. That's kind of like taking two fans and that are blowing towards each other and pushing them face to face. You know, we'd say that if you try to press the faces of two fans blowing into each other together the force of the air would oppose that. But if you imagine it in terms of these rings of air flow, is, when you try to push two fans face to face together or back to back, that kind of compresses up these air flow tubes and it, the whole system acts kind of like a spring as you try to push them closer and closer together. So, what happens in this metaphor, is a superconductor is kind of like the ground. It's not going to let any air move through it and a tube of airflow is going to kind of never be able to puncture the ground. It can only kind of hit the ground then move along it and then recirculate. So, this magnetic levitation effect is kind of like a hovercraft. You try to push it down on the ground if it's blowing air towards the ground and the cushion of air as air blows down on the ground will keep the fan aloft.

[26:39]

Darren: So, the Meisner effect is actually one step weirder than what we described. In a conventional superconductor, if you have this material before it's a superconductor siting on a magnet and cool it will go up, away from the magnet spontaneously when it goes through this transition. So, in a conventional superconductor all of these electrons could run around in circles because there's a field going through but it's a much, much lower energy state for the superconductor if it boots out the field entirely and only has currents on the surface canceling it.

Ryan: Right.

Darren: So, if you cool this thing sitting on a magnet it will actually just jump up all of the sudden.

Ryan: Pretty cool. Is there a way to weaponize that?

Darren: I hope not. It doesn't jump up very far.

Ben: So, one way to imagine. The electrons floating around inside this block of metal, once it starts superconducting, is to imagine it as a superfluid. So, in episode 16 we talked about superfluids and all a superfluid is is you have a liquid and it's so cold that it starts all behaving like one big quantum particle and so it has to obey the laws of quantum mechanics instead of regular mechanics. So, in regular fluids, say if you have a glass of water you can make the water in the glass spin.

Fiona: You can stir it.

Ben: You can stir it. But, if it's a superfluid you can't do that and the reason is kind of quantum mechanical. Actually the hydrogen atom is a great example of this. So, an electron in a hydrogen atom, so it can't fall onto the nucleus and collapse...

Darren: It can run around in a circle or it can run around in a circle twice as fast or three times as fast but only at specific speeds.

Ben: Yeah. And then what happens is, because it can't do it at specific speeds if you try, if you took a glass of this superfluid and you tried to spin it, the parts of the superfluid that are in the middle of the glass won't be able to spin around themselves because of this quantum mechanical effect. So what you could do, if you have a donut shaped tube full of superfluid you can get that spinning around the donut. But, if you have, like a glass or a bucket you won't be able to get it spinning. But, here's the thing, you can force it to spin and what happens if you force it to spin is it forms like a vortex. Like, you know the shape, if you try to drain the bathtub or like a tornado, right? There's a hole down the middle. If you have this fluid and it has a hole shape down the middle, suddenly it's kind of shaped like a circle. You don't have to deal with the fact that it won't be able rotate right in the middle of it. And so, equivalently, what happens in a superconductor, is, it's essentially like this fluid and just like in a superfluid where you can't quite get it spinning, you won't be able to get these electrons spinning in response to a magnetic field.

Fiona: If you try and put too much magnetic field in then in the same way that if you try and rotate superfluid you get vortices, you can get vortices in your superconductor and basically those vortices in the actual material sit at a specific locations in the crystal and it's typically very hard for them to to move and that's why if you put the superconductor in a big magnetic field, okay, once it's sitting there it has its vortices at certain positions and it doesn't want to move so it basically can't fall straight down because it would have to create more vortices and that would cost more energy so that's sort of what's balancing but also the reason that it doesn't sort of fall off to the side is actually because these vortices are stuck in place and so it's hard for it to move off the side of the field as well because it decreases the field by falling out the side, it has to come out of the system.

Darren: Fiona was talking about flux pinning, but there's a bit more that should probably be said about type two superconductors. In these materials there's another state available where the strong magnetic field you can poke holes through the super conductor, effectively. So, you have tubes where the superconductivity has been suppressed and the magnetic field is allowed.

Ryan: Really?

Darren: Yeah, and there's very strong constraints on that because all of the electrons are pairs running around this are behaving as one quantum mechanical object coherently their phase can only change by 2π360° or else they'd interfere with themselves, it wouldn't work. So, that means that the amount of magnetic flux going through one of these tubes is quantized, there's only a specific amounts that are allowed. In a superconductor this is H/2E, it's a small number but you're only allowed that or multiples of it in these holes. So, you will form a grid of these, they will get trapped if you have impurities that weaken the superconductivity in specific locations and that's what we were talking about in terms of vortices. The pinning can lead to weird things like if you have something that has flux pinning and you've cooled the superconductor over a magnet you can use the superconductor or the magnet to pick the other one up. If you have a superconductor running around a track you can turn the track upside down and run the superconductor running around under it if the flux pinning is strong enough.

[31:40]

Ryan: That's pretty cool.

Darren: Yeah, there's some really weird stuff out there.

Fiona: It's maybe worth mentioning that, you know, superconductivity is, was discovered in 1911. It was basically 40 years before people understood how the first superconductivity worked and then in the 1980s a completely new kind of superconductivity was discovered and we still don't know how that works. And so the physics of superconductivity really goes quite deep into the core of what we have understood in the last 100 years and also what we're still trying to understand about the way that quantum mechanics works in material. So it's a very complicated, when you get into the details and also very exciting field, both from the fundamental physics point of view and also of course from the point of view of applications.

Ben: So, that was great! Thank you Darren and thank you Fiona, you have pleased me. Your efforts have born fruit and that fruit is sweet. Here's some fruit. It's ah, Fiona, here's a mangosteen.

Fiona: Thank you. I love the mango.

Ben: Eat it. It's a mangosteen.

Fiona: I don't know what a mangosteen is.

Ben: It's like a, don't they look kind of like Lychee nuts?

Fiona: Alright, thank you Ben.

Ben: Ah, Darren, here's a pomegranate.

Darren: Okay, that sounds like more work. Thanks though.

Ben: Chew it! Alright. Do you know what these two fruits have in common?

Darren: Seeds.

Ben: They are super fruits. Ha! Alright, so I'd like to thank my guest Ryan North. Thanks Ryan!

Ryan: Thank you.

Ben: Thank you for coming on. I hope we didn't buffalo you with too many weird explanations.

Ryan: I learned a lot.

Laughter

Ben: That was great. Good luck with Adventure Time. Alright guys, before I end the show I want to tell you about two exciting new events. First off, we're finally selling t-shirts and swag. The nicest shirts of them have been designed by Chelsea Anderson. Chelsea has her own design business called Gearlight Illustration and Design. So, go to our website, www.titaniumphysics.com and click on the link to the store. I've set it up so that we get $3 from every item we sell. So it should be fun. Yeah. Alright, second big event. I've decided it might be fun to start an online community so my BrachioMedia buddies and I have decided to start a message board, like a forum. Remember the old days of the Internet? Anyway it's going to be fun. So, go to our website and follow the link to our forum and we'll chat about physics. If you want to talk to me any other way email us at barn@titaniumphysics.com or you can follow us on Twitter at @titaniumphysics or look for us on Facebook. If you have a question you would like my Titanium Physicists to address email your questions to tiphyter@titatiumphysics.com and if you are a physicist and would like to become one of my Titanium Physicists email physics@titaniumphysics.com we're always recruiting. So, suppose you want to listen to our show a little more conveniently. If you've got and iPod or an iPad try subscribing to our show using the iTunes store. If you have a Zune or a BlackBerry you can subscribe to our show on those doodads as well and while you're there if you could leave us a review that would be great.

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[36:17]

Ben: And then power storage.

Darren: Yeah, so if you make a big loop like that out of super conducting wire you can throw a bunch of power in there and store it. So, for instance if you put together a whole pile of solar panels somewhere in the desert but want to use the power, for instance, in the night, you could throw it into a superconducting magnet for a magnetic storage thing. Have the current run around for a few hours and then pull it out when you need it. That isn't in use anywhere that I know of but it is being seriously discussed.

Ryan: But you need power to keep the superconductor cooled, right? Do you end up in the black in such a set-up?

Darren: Ah, you have to watch how you do this. Cooling it down in the first place takes quite a lot, then you do need to throw energy in to keep it cold. I think it ends up being a matter of scale.

[37:09]

Ryan: Would it be going too deep into quantum mechanics to ask why there is a finite number of directions that they could be going in? Sounds like it is.

Laughter

Fiona: It's not so much, it's finite number of directions but that...

Darren: that momentum states.

Fiona: Yeah, so there's some...

Darren: To some extent...

Fiona: That's actually a little bit complicated because this actually has to do with the fact that the, the electrons... So remember, you know if you think about the , you remember you have this like infinite number of negative energy states but actually on a lattice, momentum is only defined up to some number. This has to do with the fact that if you move over by some amount everything looks exactly the same. And so there is actually some definite number of allowed momenta but maybe that gets a little confusing, maybe it's good to say, just like, you're filling your bathtub and there's a top, somewhere there's a surface to the water and that's kind of all you really need to think about probably.

Darren: Another way to look at this is when you have one isolated atom the states are basically angular momentum states and those are limited. There's only specific angular momenta that are possible. That's quantum mechanics, that's quantized, that was one of the first things that was found that was actually quantized. So, you've got some fixed number of states as your starting point when you put all of the atoms together you have the same fixed number of states per atom added up together. So, you've got some finite number of states available. Within the atom there are different energies and within the material they can combine in different ways to make a lot more different types of energy.

Ryan: Right. Okay, sure.

Darren: But the total number is the same. Everything that is interesting happens at the surface of the bathtub.

Ryan: That's very true.

Darren: So, the surface of the water, if you've got steam coming off it's coming off the surface. If there's a bad smell, it's coming off the surface. If you've got a bubble bath it's at the surface. The stuff down in the bottom is necessary for you to get up there but it's not really doing much. And it's kind of the same in these materials where you've got a whole pile of fermions together. For that fermion to change its properties something else has to get out of the way.
Or there has to be something empty somewhere and the only things that are empty are above the bathtub. So, the electrons that are buried down at low energies are basically vegetables. They do nothing.

Ryan: Right.

Darren: Ah, what you're interested in is what happens at the surface where you stopped pouring electrons in and that's where this interaction happens. So, if I have any sort of interaction between electrons that causes them to attract each other, even slightly, instead of just hating each other because they are the same charge, that will reduce the energy of these electrons slightly if they can from a pair. And, so, they want to be at lower energy they do this and you end up with pairs. One of the consequences of this is if you want to excite them, you know, bounce an electron off of something and change it's properties, you have to go somewhere and all of the states for it to go into are either already full or at a high enough energy that you have to break the pair first to get it there.

Ryan: Right.

Darren: Because, by forming the pair you've sort of pulled it down to a lower energy than where the states were to start with. So, you have to have some pretty strong scatterer in there to actually break the pairs and cause them to change their direction for instance.

[40:43]

Ben: Okay, um, so, do you get how this pairing up of electrons causes them to not bump into anything anymore.

Ryan: Yeah, no, I've had, what, this is, what, the third analogy.

Ben: Yeah, that's right.

Laughter.

Ryan: Are we going to put all three analogies in the podcast or just the last one that worked.

Ben: I don't know, maybe. Maybe I'll claim all the glory for myself. I don't know, we'll see.

Ryan: But yeah, I'm with you.

Ben: We're always fighting the clock on this, I don't know, anyway,

[41:19]

Ben: Okay. So here's the rule of thumb in terms of magnets and charges. If you take a charge and you run it in a circle. So, you take an electron and you make it go in a circle over and over and over, say you take a ring and you have electrons circulating, you'll end up with a magnetic field that goes straight up through the middle of that hoop and the more electrons, or the faster you have them circulating, the denser the magnetic field, the more powerful the magnetic field going through will be. So, what, equivalently, what happens is, if you try to shoot an electron right through a magnetic field the electron will end up moving in a circle, kind of orbiting the magnetic field. So, what happens, usually if you take a magnet and you put it up next to some object, if the electrons could circulate in this object, the magnet will cause electrons inside the material to kind of go in a circle. But usually because of friction and depending on how free the electrons are, they're not very good at moving in little circles in response to this magnet. But if you take a magnet and put it up right next to a superconductor, because the electrons inside the superconductor are free to move wherever they want or however fast they want, they can respond instantly to putting a magnet up to their surface. So, if you take a magnet and you put it up to the surface that will cause these electrons to circulate. And, the overall effect though, is, as these charges are circulating on the surface that causes its own magnetic field. And so the magnetic field it causes is always in opposition to the magnetic field you try to push into it. So as you push the magnetic field in, another magnetic field kind of emerges from it that keeps the original magnetic field and the magnet in your hand from puncturing the surface.

[43:05]

Ryan: I have a quick question, real quick, related.

Ben: Yes

Ryan: I saw a video on YouTube of a frog being suspended above what it said was a superconductor.

Darren: Not actually. So, the magnet was probably a superconducting magnet to get the field that large but the frog itself is neither a magnet nor a super conductor.

Laughter

Fiona: But...

Ryan: I'm with you on that.

Fiona: But the reason, the reason that the frog floats, above the magnet is sort of similar to the reason that the superconductor floats which is that it turns out that the frog is mostly made of water and water also sort of does this, that if you, if you apply a magnetic field it tries to make a magnetic field in the opposite direction. So, it's not a superconductor, the frog is not a superconductor but um, the basic physics of the levitation is the same.

Darren: The frog is, the frog is diamagnetic. It's a...

Fiona: Is the word.

Darren: It repels magnetic fields.

Fiona: So, the frog is not a superconductor but the frog is sort of like a superconductor in that sense.

Darren: A superconductor is a perfect diamagnet. It dispels all magnetic fields.

Ryan: Right. Ok.