Episode 61, "Levitating Trains"
Dramatis personae:
- Ben Tippett
- Erika Ensign
- Darren Peets
- Abby Shockley

The Titanium Physicists Podcast
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Ben: Never be afraid. There's nothing which is known which can't be understood. There's nothing which is understood which can't be explained. For over 50 episodes now, my team and I have brought you to the very frontier of knowledge in physics and astronomy. And still our mission goes on. To present you with your birthright: an understanding of the Universe. I've traveled the world seeking out a certain type of genius. Masters of not only their academic disciplines but also at explaining their research in understandable ways. And I've bestowed upon these women and men the title of Titanium Physicists. You're listening to the Titanium Physicists Podcast and I'm Ben Tippett. And now... *allez physique*!

01:11

[Intro song; *Tell Balgeary, Balgury Is Dead* by Ted Leo and the Pharmacists]

01:46

Ben: This one time when I was a child, it was my birthday. My twin sister and I were going to have separate parties, hers was in the morning, mine was going to be in the afternoon and it was a hot, hot July day. Well, my sister's party went off without a hitch, she had a Slip 'N Slide party, it was pretty sweet. But then, in the lull between our two parties, my friend and I were looking out the window and we saw something our 8-year-old brains couldn't quite identify. It was a cone of dark clouds stretching from the ground to storm clouds up in the sky. "Stupid pollution", I spat under my breath. And my friend didn't think it was pollution. He saw a more imminent danger in it and he told me that it was a skunk and I still don't know what he was talking about. But anyway, the reason you shouldn't let 8-year-olds make important decisions is because they can't even recognize a record-breaking tornado when they're staring right at it. And it was the largest tornado that had ever hit Edmonton. Pretty scary, on my birthday. Anyway, vortices, they're crazy, right? I mean, there's a kind of general fascination that we all have with them. They put them in our vacuum cleaners and we'll buy them because "yes, tornado-powered vacuum cleaner", there's big, permanent one on the north pole of Saturn, shaped like a hexagon, and that's weird, and last year something called the polar vortex made the eastern United States colder than the Canadian arctic for a couple days in the winter. Absolutely bananas. Vortices are very difficult things to talk about. And they're usually caused by rotation in some complicated dynamic system, lots of interacting parts swirling around each other. Like a slurry spinning in a blender, or bathtub water spiraling down the drain, or tornados, or hurricanes. I think we're fascinated with them because when we look at them down the axis of rotation, we see a tunnel shape. And the juxtaposition between the obvious complexity of the system and the visual simplicity of a tunnel awakens our imaginations. Like, in the Doctor Who universe, time travel comes from moving down a fiery time vortex thingy and in spacetime wormholes are often illustrated as vortices. I mean, it happens all the time. So when Darren Peets suggested the topic for the show, I was like "Yes, all those words sound fantastic". So, today on the Titanium Physicists podcast, quantum vortices in superconductors. Now, speaking of Doctor Who and Edmonton, I'm not yet sure if you've noticed but my old home city punches way above its weight when it comes to Doctor Who podcasts. For example, it's the home of my favorite Doctor Who podcast, it's called Verity! podcast and it comes out weekly and it features a collection of smart women analyzing and explaining new and old episodes of my favorite TV show! Their conversations are considerate and clever and well-moderated. Oh, it's so much insight. Anyway, nerdy podcast on the Internet or vortex, the today's guest is surely the axis all things rotate. She's the co-host of the Verity! podcast and another Doctor Who podcast, called the Lazy Doctor Who and a Babylon 5 podcast, called the Audio Guide to Babylon 5 and a Dungeons and Dragons podcast, called Total Party Kill podcast and she reads for the Uncanny Magazine podcast. Welcome to our show today, Erika Ensign!

Erika: Thank you, it's a pleasure to be here.

05:04

Ben: Alright Erika, for you today I've assembled two fantastic Titanium Physicists right at the height of their powers. Arise, Doctor Abby Shockley!

Abby: Boing boing.

Ben: Dr Abby did her PhD at the University of California Davis and she was previously at University of Paris South XI, working Laboratoire de physique des solides as a post-doc, studying nuclear magnetic resonance. And arise, Doctor Darren Peets!

Darren: [Toot Toot]

05:28

Ben: Dr Darren did his PhD at UBC and he's currently a Xide Fellow at Fudan University's advanced materials laboratory in Shanghai, China where he studies magnetic materials and superconductivity. Alright everybody, let's start talking about superconducting vortices. Alright Erika, so trains, right? The deal with trains is they're on trucks and the reason for that is it's a really efficient way to move stuff around, right?

Erika: Yes.

Ben: And the reason it's so efficient is 'cause there's very little friction. And by that we don't just mean there's stuff grinding on stuff but additionally, these railroads, they make them super, super, super smooth. The railroad trucks, they try to level them off so that you're not bumping up and down and losing any energy like that.

Erika: As someone who used to live in United States, I really wish that somebody had told President Eisenhower this, so that we would have more nice trains going across the United States instead of the highway system which, you know, in its way it's pretty sweet but not as cool as trains, you guys.

Ben: Trains are cool.

Abby: Yeah.

Ben: Okay, okay. Anyway, moral of the story is: the coolest type of trains are the floaty ones, right? Those are ones that kind of float in the air. And the idea is that they're levitated by magnetic fields. You've played with magnets before, right? Everybody has. You take two fridge magnets and you try to push them together and either they push apart or they pull together, right?

Erika: Yup.

06:47

Ben: And it has to do with how they're aligned, so if you flip two pulling together, one of those backwards, they'll push apart. Right?

Erika: Right. Well, that is if you can get them apart after you've let them slam together.

Ben: Yeah, that's right.

Abby: Yeah.

Erika: And snap your fingernails in between there.

Ben: You get your fingers snapped in there [laughs] So, in this case, what they're doing is, they're taking two magnets, one inside the train and in the train tracks and they're aligned so they're opposing magnets, kind of, and then the train will sit on the magnetic field generated by the track. And it will kind of push it up in the air, oppose gravity and you'll end up with a train that floats in midair. Which is wonderful, because it's super smooth, it doesn't rattle or bump and so it's much more efficient but also you can go way, way, way, way, way faster because there aren't little bumps and jostles. You know, if you had a normal train and you tried to make it go 300 km/h, it would probably jump the tracks.

Erika: So, are the entire tracks just magnets? The track itself is made out of a magnet?

Darren: As I understand it, yes. I believe electromagnets.

Abby: And then the train is a superconductor.

07:45

Ben: Okay. Before we go on. There are various different configurations that you can make one of these out of and one of the sexier and more popular ones is to use superconductors. Have you ever heard of superconductors before?

Erika: I have heard the phrase "superconductor" and I feel like many years ago I read an article that kind of explained what it was. But that was a lot of years ago and a lot of brain cells ago. So I'm gonna be honest, I don't really remember the basics even of what superconductors are. So, I'm glad I'm here with you, guys, to tell me what the heck I've forgotten.

Ben: Well, these trains go like 400 - 500 km/h, right?

Darren: And they're driven by Clark Kent.

Ben: That's right.

Darren: That's why it's a superconductor.

Erika: Gotcha. I like it already.

Ben: Okay, so, there's a really popular demonstration of superconductors that you can see if you go to, like, a science museum. How it works is they say "here's this object" and it will be like a black disk. And they'll take it out and they'll pour liquid nitrogen on it and get it really, really cold, so there's mist coming off it and then they'll take a little square of some material or another and they'll put it above the superconductor and it will just sit there, in midair. So, essentially, that's what's going on in the train. The thing that they pour the liquid nitrogen over, that's called the superconductor, it's a material with a very specific property with when it comes to how it interacts with electromagnetic fields. And then if you take a magnet and put it on top of that, what'll happen is, the superconductor will repel the magnetic field and the magnet that you put above it will just kind of float on its own magnetic field, like a spring. So that's a demo that you often see around town and once you're told that it exists, you will keep an eye out for it because they're really popular. Anyway, so that's how these trains work. They make the tracks emit a magnetic field and then above it, they make the bottom of the train superconducting and that superconductor pushes against the magnetic field emitted by the track and it holds it aloft. And it's really sexy because it's energy efficient and also really cool.

Erika: It sounds like magic but I'm certain that it's actually science.

09:47

Darren: A superconductor is a material that below some specific transition temperature it has zero electrical resistance and it wants to exclude all magnetic fields. That's the basic description of what it is.

Erika: Yeah, I feel like when I've read about it I remember the electricity part but I didn't remember anything about the magnetic part which sounds pretty important. So, I'm glad I know.

Abby: Yeah.

Darren: It's how they know it's a new phase of matter. Once they saw that then they knew they had a new phase of matter for sure. A perfect conductor won't do that. A perfect conductor will shield changes in magnetic field, it won't shield the field itself. This thing, if the magnet's actually sitting on the superconductor when you cool through the transition, it will kick it off.

Ben: Oh, really? Fantastic. Okay, let's talk very briefly about the relationship between these two. Superconductors work because of quantum mechanics. And so explaining how it all happens is actually a little bit/

Abby: They're hard to understand.

10:45

Ben: We're gonna try to do it. But before we get there, what's a conductor? What is conductivity? Darren mentioned the word earlier. It's when electrons can pass through a material really, really easily. So some materials are insulators and some are conductors. Metals are really good conductors.

Abby: Like copper.

Ben: That's why we make wires and electronics out of them. It's because we can send electrons down them to power our lightbulbs and fancy computers really, really easily. Because essentially, on its journey from the power plant down to our house, the electron, as it passes down the material's gonna bump into atoms along the way. And every time it bumps into stuff, it loses a little bit of/ it heats the material up a little bit. So, the more resistance a material has, the more heat gets generated when you put a current through it. So, some materials, when you put current through it, they don't heat up very much. Others, they heat up quite a bit.

Erika: Makes sense.

11:39

Ben: So, metals are specifically fantastic, 'cause they have really, really low resistivity. They have high conductivity. Electrons can pass through them really, really easily. So now, I wanna talk about relationship between what electrons do and magnetic fields. 'Cause there's a relationship between the two and it's not really something that you hear about because, I mean, people are used to talking about magnets, you can watch YouTube videos about magnets, go to the magnet store. It has that whole "opposites attract" thing. On the other hand, we know that electricity works via electrons moving around and bumping into things. There's a relationship between magnetic fields and what electrons do in them. They form two parts to the same big complicated system. The thing you need to remember is: an electron, when it's trying to pass through a magnetic field, won't get all the way through, it'll go in the circle.

Erika: Oh.

Ben: So, you've seen drawings of magnetic field lines, usually we illustrate them with lines, right?

Erika: Mhm.

Ben: There's all like a forest of parallel lines. You can imagine it in more dimensions. Say, the magnetic field of the Earth coming down in a bunch of parallel lines. Imagine it as a forest, sticking up out of the ground. Magnetic field coming out of the ground. And electron trying to pass through that forest, instead of running straight through between all those trees, what it'll do is as soon as got into the forest it would hook its arm around a tree and end up going in a circle around that tree.

13:05

Erika: Woah. Okay.

Ben: It's a really weird phenomenon but it drives a whole bunch of things, like northern lights. The Sun emits charged particles as part of its daily puking off of/

Darren: Stuff

Ben: /hot gasses. And when they hit the Earth's magnetic field, what'll happen is they'll get stuck on the Earth's magnetic field and they'll ride the magnetic field up to the North Pole or South Pole. And so as that radiation enters the atmosphere, it's going to enter at the North and South Pole, which is why northern lights, *aurora borealis* and *australis* are centered around the magnetic northern and southern poles.

Erika: Wow. We actually took a drive last night to look for northern lights and didn't find any, so [laughs]

Ben: One never sees them when one looks, I find.

Erika: Yup.

Ben: So, the big trick here is: if you have a piece of metal and you put that piece of metal inside a magnetic field, the electrons passing through the metal will respond to, you know, they'll be jetting from the power plant down to our house or something, they'll be moving *en masse* like bison through the metal, they'll respond to this magnetic field by going in circles. It will mess up the direction they're travelling. But the crazy, crazy thing is if you take a piece of metal without any current in it, without any electrons moving from one side/ all the electrons are just kind of sitting around and you put that in a magnetic field and you change the strength of the magnetic field, that'll cause the electrons in it to go in circles. It's this weird back-reaction thing. An electron moving in a circle is actually what generates a magnetic field and vice versa. Okay, so you've seen electromagnets before. They're coils of wire. You know, sometimes kids make them out of like nails and loops of wire. The deal is if you drive electrons in a spiral pattern around a nail, electrons moving in a circle will generate a magnetic field. So you can make a concentrated magnetic field by making a coil of wire where the electrons passing through the current of electrons passing through will end up going in little circles. And forcing them to go on a little circles will generate a magnetic field down the length of the nail.

15:02

Abby: There's like a common experiment that we do to show this. If you take like a copper pipe and then you take a piece of metal and drop it down the pipe and then you take a magnet and drop it down the pipe what you'll see is that magnet will drop down much slower than the normal piece of metal did because the electrons in the copper pipe, when it senses the magnetic field, is trying to move with it, with the magnet, it makes its own magnetic field that repels it and makes it go slower.

Erika: Yeah, I think I've seen that on YouTube. I myself don't have a magnet and a pipe. But right now I wish I did.

Ben, Abby: [laugh]

Darren: Electrons are like populations. They fear change, they resist it.

Ben, Abby, Erika: [laugh]

Ben: Yeah.

Erika: Suddenly I'm relating to these electrons so much better. Thank you for putting it that way.

Ben: Okay, so the neat thing here is: there's a back-reaction. If you drop a magnet down there, what'll happen is: as the magnet gets lower and lower and lower, that will change the magnetic field in the bits of pipe just below the magnet. And that will cause electrons to go in circles round and round and round the pipe and that will generate a magnetic field in the opposite direction. And so what slows the magnet down on its journey, if you drop one down a pipe is that the electrons inside of it are kind of rebelling against the changing magnetic field, generating their own magnetic field in the opposite direction. And so it's a kind of rare thing to see and almost nobody does this experiment at home because when I do it in class, everybody's really astounded.

Erika, Abby: [laugh]

16:30

Ben: So it's kind of a rare thing to see but you actually see it in magnetic braking once in a while.

Erika: Alright.

Ben: It's a type of/ a way to slow down your car, essentially. One way to slow down your car is with kind of friction, where you take two calipers and you just make them squeeze against the plate and the friction between them slows it down. Another way to do it, though is to take a magnetic field and spin a disk through a magnetic field. The electrons in the metal disk will say "hey, this magnetic field is changing, we're gonna start spinning in circles, generating our own magnetic field, and then that'll generate a lot of heat and the car's forward moving velocity will be turned in the heat on this plate". The moral of the story is: imagine you've got a big piece of metal and you've got a magnet in your hand and you're gonna drop the magnet onto the plate.

Erika: I'm with you so far.

Ben: As the magnet gets closer and closer and closer to the plate, the magnetic field it's emitting will try to penetrate the plate and that'll generate currents, they're called eddy currents, and those eddy currents will generate their own magnetic field, pointing upwards and that will buoy up and slow the fall of the magnet onto the plate. Okay, now the rule of thumb says that conductors don't like it when magnetic fields try to push through them. This is an anecdotal description of what's going on. Because really what's going on is this crazy back-reaction between the electrons swirling around inside of it and the changing magnetic field. But the rule of thumb is the conductors don't like it when the magnetic field through them changes. That said, the magnetic field through one of these materials can change easily and that's because there's always gonna be a little bit of resistance inside of the material to the electrons going in little circles. So electrons will want to move as fast as they can in a little circle to repel this change in magnetic field but something's slowing it down. There's always going to be a little bit resistance. Which is where superconductors come in. Because in a superconductor, there's no resistance at all. It's a type of material that has no resistance. Electrons can move through it without bumping into anything, without losing any energy. And so if I try to bring a magnet near a superconductor, all the electrons in the superconductor will say "hey, we don't want that magnetic field to penetrate the superconductor so we're gonna swirl around and moving in little circles we're gonna generate our own magnetic field that cancels this alien magnetic field out". And the net result is, if you look at a system where there's a superconductor and a regular magnet, the magnetic field from the magnet is never going to be able to penetrate the superconductor. It'll always kind of flow around it. And that's essentially what's happening with the magnetic field on this maglev train. The train tracks generate a magnetic field pointing up and the superconducting elements under the train resist the penetration of this magnetic field, push it up to the side, and that's what buoys the train up in the air. Does that make sense?

Erika: Yes.

Darren: Except that's not quite what the Meissner effect is.

Ben: [laughs] Right.

Darren: The Meissner effect is all of these electrons are doing exactly the same thing, they're all one quantum mechanical object acting together. And if there's a magnetic field there, they look at it and say "uh, nope; do not want" and out it goes.

19:40

Ben: What Darren's saying is that the description I gave of what happens in a superconductor would dictate that you can't change the amount of magnetic field going through a superconductor. But what he's actually saying is the rule isn't that the magnetic field through a superconductor can't change. The rule is that no magnetic fields can cross through a superconductor. Ever.

Erika: Right.

Ben: And the reason is because the mechanism for superconductivity is a lot more subtle.

Abby: Than your eddy current explanation.

Ben: Than my eddy current explanation. Because it's/

Abby: A lot more complicated than the eddy currents' work.

Ben: And that's a wonderful tangent because/ so, the description I gave you is what's called classical physics. It's explanations of how physics works before we include quantum mechanics into the mix. And like I said at the start, superconductors are fundamentally quantum mechanical objects. And so their properties are dictated by quantum mechanics and not these very general arguments about electrons swirling around. So to talk any more about what's going on, we need to talk about the quantum mechanics of superconductors.

Erika: Okay. It's probably good place to go.

20:46

Darren: So, the electrons are acting together and what's underlying this is they actually pair up and ordinarily they're not allowed to occupy the same sort of space in momentum or in the material.

Abby: Well, ordinarily - like you learned - like charges repel each other and unlike charges attract so all the different electrons should always repel each other but that's not what happens in a superconductor.

Darren: If you have any attractive interaction at all, then you can form these pairs of electrons. The pairs of electrons/ it's a different type of particle, it's now a boson instead of a fermion. They can occupy the same state together and they all want to go into the same state and just behave as one thing. So, the electrons that matter in a superconductor are all behaving exactly the same, you can describe them with one quantum mechanical wavefunction and you have a charge of twice the electron charge so it's doubled. It's a coherent quantum state and this is the low energy state but it doesn't like magnetic fields.

21:59

Erika: So it's kind of like instead of the electrons being like a mob of people it's like soldiers that have been trained very rigorously and are all marching in step?

Abby: Yes.

Darren: And if there's like a tree in the way or something they know the tree is there and they go around it. I would probably go back to the train thing. You said that you've got your superconducting train on top of a magnetic track and I just told you that the superconductor doesn't wanna be anywhere near the magnet. And you can imagine this being a problem because your train doesn't wanna be on the track. And the purpose of the track is to keep the train on it. It turns out there's actually two types of superconductors. And what we were describing is Type-I. Type-II, you can basically poke holes through the superconductivity where the magnetic field is allowed. And those ones when they've got magnetic field stuck in them, then in the case of the train, it doesn't want to go flying off the track. In that case it doesn't want changes in the field because the magnetic field is going through these vortices, these little holes in superconductivity.

23:06

Ben: Let's reiterate what Darren said just then. Let's talk about superconductors just briefly. Darren said earlier/ just imagine a brick. Inside the brick is full of electrons. These electrons at normal temperatures, each electron in the brick is doing its own thing. They're like teenagers at a high school. None of them want to do the same thing as any other electron's doing. Some of them are jiggling one way, some of them are going up and down, one of them has a mohawk. Oh, so confusing, teenagers. Superconductivity comes about by cooling down the material. So, they discovered that there are some materials where if they get really, really cold, what'll happen is the conductivity of the material will change in this really crazy way. What they expected is the colder you make something, the better a conductor it is. Which is why our computers kind of have fans on them - to kind of keep the processors cooler. So, so you take this brick, it's full of electrons, we cool it. It gets cooler and cooler and cooler and what they've found is in certain materials the electrons start pairing up. Now, each electron wants to be their own thing but as soon as they hook up, they start dating - it's called a Cooper pair, by the way. As soon as two of these electrons start dating one another, suddenly they don't care what anybody else is doing. As it gets colder, these electrons start hooking up, maybe for warmth, there's nothing else to do.

Abby: [laughs]

Ben: And suddenly we have a whole bunch of/ instead of a school full of a whole bunch of individuals, we have a whole bunch of couples. And the couples don't care what they do and so then you can make all the couples do the same thing.

24:38

Abby: As long as they're doing what their - you know - partner is doing, they don't care what anybody else is doing.

Ben: Yeah, so you can make them all go to the dance. And you'd be like "alright, all of you stupid electrons go into the gymnasium; and all of you have to go back and forth and dance to this music. All of you have to march in single file".

Abby: Ohh

Ben: And they'll do it happily because they're coupled up. That was that Bose-Einstein condensate that Darren was mentioning earlier.

Abby: That Darren was talking about, yeah.

Ben: So, that's how you make a superconductor. They're special materials, you make it cold enough and all the electrons start coupling up. And they behave in an entirely different way as before.

Erika: You know, since I'm somebody who lives in Edmonton, I completely understand this. The colder it gets, the more we just, you know, couple up for warmth and yeah, the attitude changes once winter hits. I get it.

25:23

Ben: It's a fantastic but very quantum mechanical object. Because all of the different electron pairs interact with the outside world in exactly the same way. If they were singles, they would fight with the outside world and each one would do its own thing. But as a pair, each couple will react in exactly the same way. Okay, so. Back to trains. Darren said something amazing which is, there are two different types of superconductors. There's a type of superconductor that's useful for trains and a type of superconductor that's not useful for trains. So the deal is that one type of superconductor doesn't let any magnetic field through at all. And those are bad for making trains out of because they want to get as far away from the magnets on the train tracks as possible. And sometimes that means sliding sideways off the tracks, right?

Erika: That sounds bad.

Abby: And we don't like it when lots of people get derailed off the train.

Darren: Especially at very high speed.

Abby: [laughs] Yeah.

Ben: If you think about train wheels, they aren't shaped like an inner tube. There's like an outside and then a kind of a divot and it gets narrower in the middle of the wheel, right?

Erika: Mhm

26:26

Ben: And that's to grab and hold onto the track, right? So we want magnetically something that kind of grabs and holds on to that magnetic field. So there's this second type of superconductor - it's the one with these vortices that we're gonna talk about, these vortexes. This type of superconductor it likes only one specific strength of magnetic field. So it'll say "yes, I like it when the magnetic field is this strong" and if you try to make the magnetic field stronger, it will push back and if you try to make the magnetic field weaker by pushing it, say, off the track, sideways, it'll fight against that and pull itself back on the tracks. So this second type of superconductor is better for this because it will let only a very specific amount of magnetic field cross through it. And so that's you guys yes, Type-II superconductors, that's the type we want when we're building our train.

Erika: The discerning superconductor.

Darren: Basically, in these materials, they start out like the other ones at very low field but then fairly quickly they decide that the effort required in shielding the whole superconductor from this field just isn't worth it so they'll allow some through in the middle and as you increase the field, you can put more and more of that in there but what's happening in the trains is, if you make this material dirty, then you've got specific sites that are already sort of holes in the superconductivity and the magnetic field is happy being there and it doesn't wanna move from those sites. This is called pinning. So, ordinarily those whirlpools are free to move around and you can add more and take them away and do whatever you want. When this material is a little bit dirty, they're stuck in place. And that's what you're describing. So, they do this but they only do this when they're dirty in a specific way.

28:13

Ben: So, at this point in time you're probably like "Okay, you're talking about magnetic fields punching through superconductors but earlier you said definitely magnetic field can't cross superconductors and then you said <<well, sometimes>> but you also said <<superconductors act like kids in high school>>. What's the deal?"

Erika: And then we got dirty, so I'm really liking this, you guys.

Ben: That's right. So imagine clouds, right? It's a sunny day but there's clouds between me and the Sun. So none of the sunlight is punching through the cloud to get to me, right?

Abby: Because it's too overcast.

Ben: Because it's too overcast. Let's say it's really, really, really stormy. There's thick clouds, none of that light's coming through. We can get around this rule that says that no light can go from the Sun down to the surface of the Earth without having to violate this rule that says "light can't go through the cloud". And the trick is, you make a hole in the cloud, right? Like the eye of the hurricane.

Erika: Mhm

29:09

Ben: In the middle of the hurricane, right at the center, in the middle of the vortex there's no cloud and so the light can pass through. Or if you want to, you remember that twister movie with Helen Hunt in it?

Erika: [laughs] Yes.

Abby: [laughs] Yes.

Erika: Actually, I never saw the movie but I did go on the experience ride at Universal studios so I'm with ya.

Ben: Riddle me this. In the experience ride at Universal studios, when you're inside the middle of the twister, is it a nice, sunny day? 'Cause it was in the Helen Hunt movie.

Erika: [laughs] I don't remember that they had it specifically in the middle of it but I do seem to remember that being a thing.

Ben: [laughs] Right, anyway so the moral of the story is: you have this material, this material doesn't let magnetic field through. This Type-II superconductors though, magnetic field can punch through without violating this rule that says "no magnetic fields come through" by letting in a vortex. So, in this vortex, it's not superconducting in the very middle of the vortex, just like how it's not cloudy right in the middle of one of these hurricanes. And the magnetic field can punch through. And so we have system that, broadly speaking, is superconducting, but there's little patches where magnetic fields can punch through. Does that kind of make sense?

30:21

Erika: Yeah, it does. I like the hurricane thing. That makes sense.

Ben: Okay, and now the dirty part. 'Cause the dirty part is great.

Erika: [laughs] Words to live by.

Ben: Yeah, yeah. We'll try to

Abby: The dirty part is great.

Erika: Mhm.

Ben: Okay, so where are these eddies gonna form, these vortices? Just like in, like, say a stream of water, there's gonna be places where the current doesn't pass through very well. And what you can do is make your superconducting material with little locations where the material isn't pure, where it's not a pure crystal. Maybe there's like a rock there or somebody put some gum in the middle of it while they're fabricating it, who knows? But at those locations it won't be superconducting and so those impurities will be the natural sites around which these vortices will form. And this is really useful when you're trying to make an industrial application, like in these trains, because you say "I wanna build a train that lets a very specific amount of magnetic field through that prefers the specific amount of magnetic field". How am I gonna do it? I'm gonna put a certain amount of impurities in my superconductor and that way I know how many vortices will form and where they'll form and they won't wander around. They'll just kinda be stuck and located where the impurities are and that way we can manufacture the system so that only a specific amount of magnetic field comes through and it will float a certain height above the track. Does that kinda make sense?

31:46

Erika: Mhm. Yeah. I'm picturing it now.

Darren: So, the Type-I ones that don't do this, if you put a magnetic field on, it's just "nope, not going to allow it, over my dead body" and the magnetic field, you keep increasing it and it says "okay, over your dead body" and the superconductivity is dead. The Type-II materials, we've increased the field and doesn't take it very long before it says "maybe we can find a compromise here" and you get this mixed phase where you've got holes in the superconductivity where field is allowed. So, they can usually go to much higher fields, which makes them much more useful for this sort of a thing. You wouldn't be able to levitate a train or anything heavy with a Type-I superconductor in general, because you get it near the magnet and it runs itself normal and crashes.

32:33

Abby: Or just, like sticks back down onto the track and doesn't move at all.

Darren: You don't wanna be going 500 km/h and it gets, you know/

Abby: Just falls straight down to the track and it stops.

Darren: Decides it's not going to be superconducting anymore and goes 'thump'.

Erika: Yeah, that sounds messy.

Ben: Okay, Erika, I bet I can explain in terms of high school sweethearts why that happens.

Erika, Abby: [laugh]

Erika: I love it.

Ben: So, we mentioned before what electrons do in magnetic fields, they wanna spin in a circle, right? You have two electrons, they're coupled up, they're in a little sweet relationship. You put in a big magnetic field and one of them goes "Hey, I think we should circle to the right" and the other goes "Oh no, we should go the other way". It breaks them up, they react differently to the external magnetic field and that splits them up. So, this external magnetic field causes a turkey dump - a massive break-up between all these relationships and the material stops superconducting. The Type-II system, though, what it'll do is, instead of breaking them up, they'll say "How about if we kind of agree to disagree and kind of walk in a circle?" And you end up with vortices forming, letting the magnetic field through. So, generally speaking, these vortices will form as the couples decide to kind of move around as a pair in response to the external magnetic field. They'll form and like the center of the vortex will move around inside of the material. So, like imagine you've got a sink that's draining and a little vortex forms on the surface, right? Where the whirlpool is located on the surface moves around, right? Just to left, to right.

34:08

Abby: It can move like from side to side on the top but you can also get it to move like by flowing around so that it's curved instead of straight down and all of that can happen with the vortex in a superconductor, too. So what we were trying to get to is we don't like them to move that much, you wanna keep them in the same spot, like that's better for applications. So, you can put something in them like, I don't know, I'm gonna put a metal rod in the sink here and then maybe my vortices are gonna be attracted to that, you know, metal rod, and it's gonna stay there and then I don't have to worry about it moving so much.

Erika: And that's the pinning that Darren was talking about earlier.

Abby: Yeah. That's the idea. You wanna keep it fixed, so that it doesn't go do whatever it wants to do.

Erika: Makes sense.

Ben: So, why is it desirable to have this pinning happen at all?

Darren: So, one thing is if a vortex is allowed to move, you can get losses, you can get resistivity again. So, if you're running a big current through this and you have a vortex, on one side of the vortex the current is moving in the same direction and on the other side it's not in the same direction and the vortex wants to move sideways. Moving the thing around is lossy. The center of the vortex, you've punched a hole in the superconductivity, it's got resistivity, you're moving stuff. So, if you can get that to stick in one place, you don't have that loss. So, if you want to use this for power transmission, for instance, you can move electricity around without loss but you have to make sure that if you've got vortices in there, they're stuck.

35:45

Erika: Hah.

Darren: You can run a superconductor out of the superconducting state into the normal state by increasing the temperature, the field or the current. And the Type-II materials usually have a much, much higher critical current and a much higher critical field.

Erika: Which sounds like it makes them much more useful.

Darren: Yeah.

Abby: Yeah.

Ben: Do you guys want to take a crack at explaining why quantum mechanically the Meissner effect works?

Darren: Ooh, my turn, my turn? I've got a couple of things I want to explain in here. So, I mentioned that this superconductivity is one coherent quantum thing and there are two length scales that are important - two distances you have to think about. One of them is, if I've got this in a magnetic field, it's shielding the magnetic field from the center with a current that's running around the outside. And that current decays in, so the field also decays in and it decays in with some characteristic distance. That distance is called the magnetic penetration depth. If I perturb the superconductivity, if I put a hole in it, an impurity, something like that, in the middle. The superconductivity is maybe 0 because it's going around this, there's no superconductivity at this impurity or hole or whatever but then the superconducting wavefunction recovers back to full whatever, independent of current - there doesn't have to be any current there at all. It's just the wave function recovering on its own. That's a different length scale, called the coherence length. So, if I have a situation where the coherence length is small, this is Type-II. If I put a hole in the superconductor, it recovers really quickly. It doesn't care so much. And then the current is spread out and I don't have some concentrated current because that length scale is much longer. So that's not much of a problem either. So it's not really that much of a problem if I've got a hole in this and current's running around in the circle. That's where I've got the Type-II superconductor. In Type-I it's the other way around, so there's a huge energy cost of doing something like this because the superconductivity doesn't come back very quickly and the currents are very concentrated. Now, the other thing in here is in the math, in the quantum mechanics, the magnetic field enters in a specific way that affects the phase of the quantum mechanical wavefunction. And ordinarily, this is something that you don't care about and can't measure. It's like technically it exists but it has no meaning. But in this case when you go around this bit of magnetic field, the phase changes continuously. So when you go around in a circle, this is all one coherent thing so you have to get back to where you were. It has to change by 2π or 360°, if you prefer degrees, or that times some integer. So, that means that you only allowed a specific amount of field in there and the result of this is that the magnetic field in this hole is quantized in units of $h/2e$. $2e$ because you've got two electrons in a pair. So, these things are actually quantized field - you've got this quantum quantization quantae, whatever. So you can have a whirlpool that's size 1 or size 2 or size 3 but not size 1.7

39:07

Ben: So, Erika. That must have been a little bit overwhelming.

Darren: I didn't start with once upon a time. All good stories start with once upon a time, that's the problem.

Ben: We can talk about the problems that are associated with dealing with magnetic fields in a system in terms of kind of what the couples of electrons are doing.

Abby: Are we going back to high school again?

Ben: Yeah, I'm trying to.

Darren: But they're trying not to walk through trees. They wanna go around the trees.

Ben: The thing to know here about our high school full of teenage couples is, like, uniformity is the thing to do with these teenage couples. They're all essentially acting exactly the same way.

Abby: Exactly the way that we don't expect teenagers to act.

Ben: Yeah but because they're all coupled up, they all do that thing that teenage couples do which is, you know, as soon as you turn off the light, they start making out. As soon as you're not looking, they start holding hands. Dynamically, each couple acts the same way. So, effectively, you don't have a high school with 200 couples, you have essentially a high school with one single couple that's 200 times the size of a regular couple.

Abby: Yeah.

40:19

Erika: [laughs] Yeah

Abby: So, that theory that he's talking about, like the wider name for it, is called emergent behavior and it's seen in a lot of things besides, like physics and electrons. I don't know in high schools yet. The most common example that I hear is birds flocking. Like, each bird by itself is sort of doing its own thing but if you look at the birds that are flying in a very large group of birds, they usually form some sort of pattern, even though they didn't, like, get all the birds together and say "hey, let's fly like a V" or whatever.

Ben: The thing you need to know is that essentially you've got a high school with one couple in it. Essentially one single particle called "a teenage couple". And it's 200 times the size of regular teenage couple. But it acts like one thing.

Erika: Sounds like a movie from the 50s, I'm with ya.

Ben: Exactly like a movie from the 50s. Now/

Darren: Are we going to get into particle theory and talk about the exchange of lessons among morons?

Ben: No, that sounds fantastic, though. So, remember early, early, early, at the start of the show I was like "you take a magnetic field and you change it, the magnetic field, it'll make electron do a little circle", right?

Erika: Mhm

41:29

Ben: Implicit in that argument that something is going in a circle is kind of that there's a place that isn't moving in that system, right? The center of the circle. There's a location in that system that isn't spinning.

Erika: Mhm.

Ben: So, the thing about our high school that's just one giant glob of student that's making out with itself, it you try to punch that with a magnetic field, its immediate reaction is "oh, I'm going to spin in a circle" but because it's essentially one big glob, it can't figure out what the center of that circle's going to be. So it won't spin.

Abby: Like a really bad high school dance that you're explaining.

Ben: Yeah, yeah.

Erika: It's terrible.

Abby: Yeah.

Ben: But here's the thing. All you need to do is you need to you just need to put something in the middle that won't move, you puncture it. You say "here's a part that won't be rotating" and then as soon as you put a chair in the middle of the dance floor that defines the center, everything else can start moving around it and rotating around it. And so you won't get magnetic vortices forming unless and until part of the system decides to disengage with the rest of it and stops being superconducting. Yeah, dance floor. Oh, that would've been a great metaphor the whole time.

Erika: [laughs]

42:39

Abby: I didn't think about it until you started talking about people making out and spinning around and then I was like "Oh, high school dance".

Ben: So, it's like this high school dance. If you put it in a magnetic field that's analogous to everything moving around the dance floor.

Abby: But the teachers come in and one put (...) between you.

Ben: That's right. Because this is just undifferentiated mass, nobody knows where the center of the dance floor is. Nobody knows where to start circling. And so if you break that symmetry up by essentially making Janice and Terry break up, you go "okay, these two people aren't dancing anymore, they're standing still", everybody else can now move in a circle around them. And that's how the vortices form. Does that kind of make sense?

Erika: Yeah. Yes, the dance floor analogy is working for me.

Ben: Yeah. So, everything else that isn't the chair in the middle, that isn't Terry and Barbara, the mass of other students who are still one big 99-student-sized couple, it essentially skips acting like one big object. And so as it moves around the center, it's going to have to move in a way so that it doesn't step on top of each other's foot, it doesn't cross itself. The result being that you end up with discrete amounts of magnetic field that you can put inside the center of it and so you can have one unit of magnetic field or two units of magnetic field or three units of magnetic field but not 2 and a half units of magnetic field. And that's what Darren was talking about.

44:04

Abby: He was talking about a really awkward high school dance.

Ben: He was talking about a really/ where everybody takes out their calculators and/

Erika, Abby: [laugh]

Ben: Okay, Erika, do you have any questions?

Erika: There was a lot of things but I think they all sort of started to come together. You know, once we got back to high school, you know. High school just puts me in the frame of mind for learning and awkward, you know, dancing, of course. So, yeah.

Ben: So, moral of the story is if you get everybody in your high school hooked up because of the nature of teenagers they'll react like one big teenager.

Darren: At least if they're cold.

Ben: You can't have dance without having at least one couple in the center.

Abby: But you have to have the air conditioning on really high.

Erika: [laughs] Yes. The gymnasiums are always pretty cold, so.

Abby: Depending on the season.

Darren: We didn't really mention if you don't have strong pinning, these vortices like to form some sort of an ordered structure like a triangular lattice. Sometimes square lattice. Usually triangles.

45:03

Abby: They like patterns, they like to dance in patterns like it's an old school square dance or like an 1800s, 1700s like Victorian thing where you all have to dance in lines.

Erika: Yes, like the minuet.

Abby: Yeah, exactly.

Ben: Well, that was fun. Thank you Abby, thank you Darren, you've pleased me, your efforts have borne fruit and that fruit is sweet. Here's some fruit. Abby, you get a pomegranate!

Abby: Yum Yum Yum

Ben: You gotta make eating sounds.

Abby: Oh, that is my eating sound. Why can't that be my eating sound?

Ben: Alright, okay, okay. Darren, you get a durian.

Darren: Yay, sorry everybody.

Abby, Ben: [laugh]

Ben: I'd like to thank my guest, Erika Ensign, from the Verity! podcast and many other podcasts. If you want to listen to her other podcasts, you can go to our website and I'll have a list of all the different places you can find Erika on the Internet. Thank you very much, Erika!

Erika: Thank you so much for having me. This has been fascinating.

Ben: Alright.

45:59

Ben T: Oh wow, that was fun. So many learny things, so many complicated metaphors. Hah, dancing, all that. I had fun, I hope you had fun. Okay everybody, it's time for announcement time. First on the list, please give us an iTunes review, 'cause giving iTunes reviews raises up in the charts. Or you can tell other people about us online in different ways like Twitter or Facebook or whatever. Why do we want you to do that? It's because people keep their deep love of physics secret. They want to know that there is a show like ours online but they don't know that we exist. A subset of your friends and family will be happy to hear about us and then you'll have somebody to talk about physics to. Anyway, on another note we're still humbly soliciting your donations. Your donations go to pay server fees and also our ambitious project to get all the episodes transcribed. You can send one-time donations through PayPal off of our website or you can go to our sweet Patreon site and give maybe a two dollar donation that gets recurringly charged to your credit card or whatever. This particular episode of the Titanium Physicists has been sponsored by a collection of generous, people. I'd like to thank Shlomo Dlal, Melissa Burk, Yaseen Owarzazee, Spider Rougue, Insanity Orbits, Robin Johnson, madam Sandra Johnson, Mr. Jacob Wick, Mr. John Keese, a Mr. Victor C., Ryan Close, Peter Clipsham, Mr. Robert Halpen, Elizabetha Theresa, Paul Carr. A Mr. Ryan Noule, Mr. Adam K, Thomas Shayray and Mr. Jacob S. A gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, Mr. James Clawson, Mr. Devin North, a gentleman named Scott, Ed Lowlington, Kelly Wienersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Aberzado and Mr. Robert Stietka. So, that's it for Titanium Physicists this time. Remember that if you like listening to scientists talk about science in their own words, check out the Brachiolope Media Network. It's our network, we helped start it and there are lots of other, sciency shows on it where scientists talk about science in their own words, absolutely fantastic. The intro song to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. So until next time good day, my friends, and remember to keep science in your hearts.

48:39

[Outro song; *Angela* by John Vanderslice]