Episode 16: Drinking Superfluid from the Fire Hose of Knowledge
Physicists: Jocelyn Read, Fiona Burnell

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]

If you have a bottle of water vapor with a pressure around sea level and you cool it, the vapor condenses to liquid water and if you cool it even further it turns into a solid, ice. Now, if you have a bottle of pure nitrogen gas with a pressure around sea level and you cool it to about -196° C it will turn into a liquid and if you cool it down another 15° C to -210° C it will turn into a solid. Same thing for oxygen. At -183° C it turns to liquid at -219° C it turns into a solid. Okay, so what about helium? The story goes, at about 3 or 4° K, that's 3 or 4° above absolute zero, helium gas turns into a liquid. And then, no matter how cool you make it it doesn't turn into a solid. At least not when it's at a pressure around sea level. If you get it cold enough though it gains really strange attributes. It becomes something called a super fluid. Superfluids have strange properties. For one, they don't have any viscosity. In laymen's terms, that means there's no thickness to them. They flow without friction. So, as a result they can pass through tiny cracks so you can't stop it with a cork you also can't paddle a canoe in it or if you got a bucket of it and you spin the bucket the fluid won't spin around with it. So, it's absolutely crazy stuff. Today we're going to be talking about superfluids. Alright my guest today is the fantastic author Kelly Link. She's definitely one of my favorite short story writers and she's got three collections of short stories and they've won Nebulas and Hugos and World Fantasy awards. Her collections are titled *Stranger Things Happen*, *Magic for Beginners*, and *Pretty Monsters.* Now, the first one, *Stranger Things Happen*, is available online under Creative Commons copyright so if you want to download it and read it you can. Her stories titled *Some Zombie Contingency Plans* and *The Hortlak* have been read on the Podcastle Podcast if you want to try listening to it. Hi Kelly Link, welcome to my show.

Kelly: Hi. Thank you very much.

Ben: Today I've brought for you two of my wisest Titanium Physicists. So, arise Dr. Jocelyn Read.

Jocelyn: Raaaaaaaaarrrrrrrrr

Ben: Very good. Dr. Jocelyn did her undergraduate at UBC and her PhD at the University of Wisconsin, Milwaukee. She's currently at the University of Mississippi working on neutron stars but she'll be starting as a professor in the fall at Cal State University Fullerton. Alright, now, arise Dr. Fiona Burnell.

Fiona: Boink.

Ben: Dr. Fiona did her undergraduate at UBC, her PhD at Princeton and she's currently a condensed matter theorist at Oxford University.

Okay, so let's start talking about the very basic property of superfluids which is superfluids don't have any viscosity. Imagine you've got a glass of water and a milkshake in front of you and you have a variety of different straws. So, you want to drink the milkshake, you have to take a fairly wide straw, right? Because if the straw's too narrow you won't be able to suck the milkshake up through it. In essence, the viscosity of the milkshake is higher than the water. So, you'll be able to drink the water with a narrower straw that you would be able to drink a milkshake out of because of the viscosity of water, the thickness of water is much lower than the viscosity of the milkshake.

Jocelyn: Viscosity is how quickly the fluid, I mean, so it's a fluid that's taking the shape of whatever is holding it. It just flows to take the shape of its containers. And the viscosity says well how quickly does it do that. How good a fluid is it. If it was a perfect fluid it would be very quickly just going exactly into whatever you poured it into.

Kelly: Okay. I, you know, I know that this is not an exact metaphor but I'm kind of thinking of a weird CGI technique in which you have the sort of liquidy silver stuff which often in movies is very slow but...

Ben: Right, so, like the Terminator.

Kelly: Yes, if you were to pour the Terminator and he filled a jar very quickly.

Ben: Right. So, contrasting with the Terminator, a superfluid doesn't have any viscosity. And so, what it means is, you could suck it through any sized straw you want.

Kelly: Okay. I was going to ask if it is affected by gravity. You know, what affected gravity had.

Jocelyn: Well, it's still affected by gravity the same way as regular fluid is. It's just that what happens is that some of the way we usually think of the balance between gravity and fluid behaviors is going to be different because the gravity is the same per mass of superfluid but the fluid behaviors are different.

Kelly: So, maybe some of the ways in which we think of gravity, those are actually attributes of viscosity? If I'm watching a fluid fill something and it it sort of taking a period of time, I don't necessarily think in terms of viscosity typically. I think more...

Jocelyn: It's more like comparing, say, honey to water. If you're trying to fill a honey bear it kind of, there's kind of a lump of honey and it maybe doesn't get into all the crevices and then it slowly oozes into the crevices and slowly flattens out. That's the viscosity of honey.

[6:55]

Kelly: So, no ooze.

Jocelyn: No ooze in the superfluid.

Ben: No ooze in the superfluid.

Jocelyn: It's ooze free.

Ben: It has attributes like, you know how, you can stick a cork in the top of a bottle and if the bottle is full of water you can turn the bottle with the cork in it upside down and the cork will stop the water from flowing out. And it does so because, I mean, there are little cracks in the cork but the viscosity of the water is such that it can't quite move through the narrow narrow cracks. On the other hand, if you have a superfluid and you fill a bottle of wine with the superfluid and you put a cork in it and you turn it upside down the superfluid will be able to pass through those little cracks and so a cork isn't enough to stop a super fluid. So, this process is called superleaking.

Laughter
Kelly: I didn't know that.

Ben: It's kind of aggravating because there's all sorts of vessels for fluids that we're used to using like ceramic vessels where we just assume that the liquid won't be able to pass through the narrow, narrow pore size but superfluids can just leak right through it.

Kelly: So, through the bottom of a ceramic container.

Ben: That's right. They superleak.

Jocelyn: So, all the tiniest little holes that the water kind of gets clogged up on itself through. The same way you can't pour honey through a small straw.

Ben: Okay, yeah, so, earlier you asked a question about gravity and it's interesting because superfluids have a reputation for defying gravity and the way it works is kind of neat. It's a little easier to understand than you'd imagine. So, what happens when you put a fluid inside a container is often the fluid will kind of wick up the sides of the container.

Jocelyn: Like if you're cooking and you need to measure out a cup of water you have to be careful because the water kind of curves up on the sides of the measuring cup.

Kelly: Yes, okay.

Jocelyn: And then in the middle it's flat. So that little curving up on the sides is happening because the fluid of the water actually likes to stick to the glass more than it likes to stick to other water.

Kelly: Alright. Okay.

Ben: So, what will happen with superfluid helium is imagine you have a bucket of this stuff. It will wick up the sides of it just the way a regular fluid might so there's a thin layer of these atoms stuck to the outside and it will wick all the way up and down the outside. And I'm sure you know what a siphon is, right? You kind of siphon gasoline, you have a tube...

Kelly: Do you now?

Ben: You go to the gasoline tank in a car and once you suck enough gas through the hose and bring one end of the hose lower than the tank of gasoline say, the gasoline will flow out to the tank, through this pipe, even though it's going up hill and down hill, the difference in pressure between the two sides drives the fluid uphill and downhill so that you can get all the gasoline out of the gas tank.

Jocelyn: You can also use it to clean fish tanks in a less potentially criminal analogy.

Ben: Oh, yeah, I've done that too. Well, that's messy, you end up with fish crap all over.

Jocelyn: Wait, when have you been siphoning gas out of gas tanks.

Ben: I've been watching a lot of trailer park boys lately. So, what happens, we mentioned before that these super fluids can kind of flow under any cracks.

Jocelyn: They don't like to stick to each other at all.

Ben: That's right. So, this layer of fluid that wicks to the outside of the container of your bucket can actually act as the siphon. So, once this layer is down lower than the pool of fluid inside your bucket the superfluid will kind of get sucked out under that layer and get siphoned out of the bucket. So, occasionally what happens is you have a bucket full of superfluid and it won't be made of something porous, it will be made of glass say, and the super fluid will flow up the inside walls and down the outside walls...

Kelly: Then flee the building.

Ben: Then flee the building. Right.

Kelly: Superfluid is sounding like an extrovert. If a liquid is an introverted or extroverted sort of thing this is sounding like the kind of fluid that likes to make friends, go places, doesn't stay at home.

Fiona: Difficult to keep at home, yeah.

Jocelyn: The whole thing is, with a superfluid compared to a regular fluid, so a regular fluid is like a collection of normal humans. Right, so Fiona was talking about this analogy earlier, if you're like looking up over say a big stadium full of people and you want them to all go in a particular direction, they're kind of bumping into each other, they're, you know, they can't just all move smoothly and that sort of causes a viscosity of people.

Kelly: Okay. So if...

Fiona: It's like if you have a big crowd, you know that, like if you go to an amusement fair. I have this vivid memory of being at Expo in 1986 in Vancouver and getting lost in this big crowd of people, right, and you know that somewhere on the other side your friend is waiting for you and you're late and you've got to get across but there are all of these people in the way and you have to go around all the people and it takes way longer to walk across than it would if there was nobody there.

[11:41]

Jocelyn: What happens with a superfluid is the superfluid is like all the atoms forming the fluid are locked together in this sort of mind meld like the Borg.

Kelly: Right.

Jocelyn: So, if the Borg collective wants to exit a stadium they all move together in a very streamlined fashion. They're not randomly bumping into each other because they all know where they're all going together.

Kelly: Okay

Jocelyn: And they just move as one entity.

Kelly: So then, I do have a question about the bucket then, which is that if you have your superfluid in a bucket is it equally sort of wicking over the sides in all directions? Does it all wick, sort of, coating equally all around the perimeter.

Ben: As I understand it depends on the geometry of the bucket. So, different buckets it works differently. If your bucket has a rounded top the wicking fluid will be able to get over it really easily whereas if it's a really jagged top, like if you put a razor blade around the edge of your bucket, it will have trouble getting over that razor blade because you won't be able to make a nice, smooth transition.

Kelly: Okay.

Ben: And so, the superfluid will drain out of a sharp bucket slower than rounded bucket.

Kelly: Okay. You're making me really wish that I had a couple of buckets of superfluid, it sounds like fun.

Ben: Oh, yeah, it definitely is fun.

Jocelyn: There's some great YouTube videos.

Kelly: Okay. Alright.

Ben: Um.

Fiona: Have we discussed all of the attributes that you wanted to discuss?

Ben: Yeah. Here. Let me see. Okay, right so if you try to paddle a canoe on top of the superfluid it wouldn't work.

Kelly: Huh.

Jocelyn: Because all of the Borg sees the paddle coming and smoothly moves around it and onto the other side.

Ben: Yeah, that's an interesting distinction. So, imagine if you were a giant and you decided to go canoeing on an ocean of people.

Kelly: In a mosh pit!

Ben: You're a giant and you're trying to paddle your canoe on a mosh pit. In the front and the back of the paddle. The back is the direction you are pushing in and the front is the direction you are trying to go. Right. So, on the back of the paddle you're going to get an over concentration of people and near the front of the paddle you're opening kind of a hole.

Kelly: The people are trying to run away but they can't because there's other people in the way, so they're just getting.

Ben: That's right.

Jocelyn: They're running into each other. Viscosity all over again. They're interfering with each other.

Ben: Yeah, so they'll try to go from the over concentrated region to the hole that the front of your paddle has made and kind of even themselves out.

Kelly: Right.

Jocelyn: We need a soundtrack of screams for this analogy.

Ben: Because this pile of people is so bad at communicating because they're kind of all at sorts, there's a lot of wasted effort. And this is kind of viscosity, this is the thing that you're pushing against when you're paddling your canoe in a regular fluid.

Kelly: In a regular fluid you're paddling your canoe against people so to speak. Unorganized people.

Ben: Right. When you try to paddle your canoe in the ocean of Borg people what happens is they see the paddle coming and then in a coordinated effort they kind of file around and fill in the space in front of the paddle and remove themselves from the place that you're paddle is trying to push against. And so the effect is that you can't really push against it.

Jocelyn: They don't interfere with each other so they can just move around as needed to respond to whatever is changing in their environment.

Kelly: I'm picturing again, the superfluid as this sort of being a group of very organized dancers, you know, who are choreographed to such an extent that they get out of the way or else, almost sort of, martial arts, where, by the time that you put your paddle in they're already out of that space.

Ben: Right.

Kelly: Or moving out of the space very quickly.

Fiona: It's a team performance. I think the analogy of a troupe of dancers is a good one. So there's a whole bunch of people on the stage and each one knows somehow, exactly that moment, you know, what the next person is going to do so they can move around in a complicated way but not bump into each other.

Kelly: Okay, alright.

Jocelyn: Actually, I have another martial arts analogy. You know, say you're a fluid and you don't want to be paddled. One of the ways you could stop is be a really resistive, thick fluid. So, you know, you can't paddle your canoe in peanut butter.

Kelly: Right

Jocelyn: The peanut butter is like the karate block.

Kelly: Okay

Jocelyn: It will not let you move. The superfluid is the Tai Chi master of fluids so you try to paddle through the Tai Chi master and it just moves past you. So, you push and it's not stopping you from pushing but it's just sort of sliding around your push.

Kelly: So, it's right there, it looks like it's in range but it's evading you at the same time.

Ben: So these are just a few basic properties of the superfluid. You have superleaking, right, so it can pass through any size crack available. You have this wicking where it wicks up the sides then flows out of your bucket. Ah, you can't paddle it and then a third one is actually kind of interesting, it's that if you try to make it spin gently, like imagine you have a bowl of soup and you kind of spin the bowl of soup eventually the soup will start rotating along with the bowl.

Kelly: Hmmm hmmm.

[16:24]

Ben: You can't do that with superfluid. So this is another fundamental aspect of, amongst all of these features of the super fluid come from the fact that it has kind of a quantum mechanical nature. So, a superfluid is one of these very unique situations where the really weird world of quantum mechanics is affecting properties that are macroscopic. Usually when we talk about quantum mechanics you need like a particle accelerator or something really small or something really high energy. But with superfluids you just need something cool enough and you end up with a big bowl of quantum mechanics. So, let's talk about making helium superfluids. Most of the discussion I've seen involves helium. That was the first superfluid discovered. But the issue here is that there's two types of helium isotope. Are you familiar with isotopes Kelly?

Kelly: No, I'm not. I was about to ask.

Ben: So, an atom is made up of an electron part so there are electrons flying around on the outside. And there there's a nucleus part.

Kelly: Okay.

Ben: The nucleus is made of two different types of particles. There are protons and neutrons.

Kelly: Yup. Okay.

Ben: So the protons have a positive electric charge and neutrons don't have any electric charge at all. And they're both fairly heavy, they're of comparable mass. And so the number of protons in a nucleus determine the chemical element. So, one proton and it's hydrogen, two protons and it's helium. The number of neutrons in it doesn't really determine the chemical name of the element but it can have subtle effects because it can change the mass. So, in this case the nucleus of a helium atom can have a different number of neutrons in it. If it has too many neutrons in it a nucleus will usually decay.

Kelly: Okay.

Ben: So, plutonium has too many neutrons in it and it falls apart.

Kelly: Sure.

Ben: So, a helium atom can stably have one or two neutrons. So these two are referred to as helium-3 and helium-4. Helium-3 has one neutron and two protons. One plus two is three. Helium-4 two protons and two neutrons.

Kelly: Sure. That explains where the name comes from.

Ben: Right. So they have slightly different masses but helium-4 is slightly heavier than helium-3 but what happens is if you make helium cold enough, quantum mechanical effects start to play a major role in how the thing behaves. Helium-4 will turn into a super fluid at about 2.17° K, that's 2.1° K higher than absolute zero. Whereas helium-3 will only turn into a superfluid at 0.002° K so that's almost at absolute zero. You have to get much colder to make helium-3 into superfluid than helium-4.

Kelly: Okay.

Ben: Just for reference, the helium-4 transition point into a superfluid is just slightly colder than the temperature in outer space.

Kelly: Okay.

Ben: So, it's really, really cold. So the reason is actually kind of subtle. We mentioned this on a previous podcast where we talked about the Dirac Sea. The reason that helium-4 turns into a superfluid really easily and helium-3 doesn't is because, in essence, 4 is an even number and 3 is an odd number.

Kelly: Okay.

Ben: And it's crazy because there are two different types of particles. There's ones called fermions and there's ones called bosons. And fermions are named after a guy named Fermi and bosons are named after a guy named Bose. So, they're not descriptive at all. So, fundamentally the first rule, when you're imagining quantum mechanics is that stuff can pass through other stuff, right. So, we don't need to imagine things bumping up against each other.

Kelly: Okay.

Ben: But the world is full of stuff. So the thing about fermions is that they're like tennis balls, you can't make them occupy exactly the same place heading in exactly the same direction right. You can't make two tennis balls overlap continuously. You can make them cross but you can't make them overlap.

Jocelyn: These are weird tennis balls that can pass through each other but they just don't like to be going the same direction at the same time.

Ben: That's right. Whereas ghosts, ghosts can stand inside of each other for as long as they want.

Kelly: Okay.

Ben: So, bosons are kind of like ghosts, they pass through each other and don't care. So, essentially what happens at really low temperatures is if you have a collection of fermions, they're like these tennis balls stacked in a box. You can kind of pile them into the box and you can close the lid but there's like, they're always going to kind of, fill up a volume, whereas these ghosts, you can put as many ghosts in a box as you want. You can always pile more ghosts in and it would just increase the quantity of ghosts. So effectively when you lower the helium-4 down to really, really low temperatures all of these, they kind of move like ghosts. You can pile them all down into the same quantum state. I refer to quantum states as kind of a hand wavy thing but there is kind of a description for how a particle can interact and all these different bosons can evolve in exactly the same way.

[21:25]

Jocelyn: I just wanted to say, that this kind of explains this collective Borg behavior. It's not that they're all psychic with each other, it's they're actually, they're all the same quantum state. They're really behaving together as a coherent whole in a really sort of fundamental way. So, it's not like they understand each other by passing messages but they're all the same thing, they're really epitomize the Borg ideals.

Ben: It's like a, it's kinda like a choir that's all singing one song. They might evolve but they're all evolving in exactly the same way and they are moving as a coherent whole instead of...

Kelly: Okay.

Ben: As individuals. Okay, so we talked about bosons and fermions. There are bosons and there are fermions and it turns out that helium-4 is a boson and so if you cool it down cold enough it turns into a superfluid.

Kelly: Okay.

Ben: Okay. So...

Jocelyn: It's a boson because it's got two pairs, I mean it's got pairs of all the components. So, even though individually they're fermions they pair up to bosons.

Fiona: He was talking about the neutrons and the protons actually.

Jocelyn: Oh, sorry. There's the two and two.

Fiona: But that's maybe another layer of complexity.

Jocelyn: Sorry, yeah, ignore that, ignore that.

Ben: That's fairly complex.

Kelly: I understood that part. I understood that part.

Ben: Yeah, I think I might leave it in. After all, I did say that there's three nucleons and four.

Jocelyn: Yup. One plus two and two plus two, yup.

Ben: That's where it all comes together. Essentially the behavior of this bucket of of fluid is quantum and you get one really crazy consequence which has to do with the fact that if you have a bowl of it and you try to spin it you can't spin the bowl of...

Kelly: Okay.

Fiona: You can spin the bowl but you can't spin the helium.

Ben: Right.

Fiona: So, I have my bowl. Well, I guess I can't really have a bowl, it's a bowl with a top on it, okay.

Kelly: Okay.

Fiona: But the top is clear so I can see through it and I can turn the container um, but you know if you did this with a container of water, basically because water is sticky, and it sticks to the sides of the container and it sticks to itself, the water would start to turn as well.

Kelly: Sure.

Fiona: So, instead of stirring your soup you could take the pot and spin it around it you really wanted to. But in this case, you know, basically because the superfluid is not sticky, you will turn the container the fluid will just sit there. As long as you don't turn the container too fast.

Ben: In essence though there's some small print when we say that you can't spin a bucket because, imagine you have like an inner tube for a bicycle tire.

Kelly: Okay.

Ben: So it's shaped like a donut and you filled it up with this superfluid. You would be able to make the fluid inside that ring spin and in fact the spin is kind of quantized. So, you wouldn't be able to spin it at an arbitrary speed, there's just kind of a number of different speeds that you can spin it at. So it's kind of like, you can spin it at 1 KM/hour, or you can spin it at 2 KM/hour, or you can spin it at 3 KM/hour but you couldn't spin it at 2.5 KM/hour.

Kelly: Okay.

Ben: I guess is what they're getting at. And the difference is between the bucket and the inner tube is that the inner tube has a hole in the middle of it. So, what happens is, if you've got a big bowl of superfluid you can kind of get it to spin but if you do it by making little tornadoes of fluid. So, you know, imagine a tornado, or, even, imagine you're draining the bathtub.

Kelly: Yeah.

Ben: And as the water circles the drain there's a little hole straight down the middle.

Kelly: Yup.

Ben: That's a vortex. In a vortex there's kind of a big hole in the middle the same way there's a hole, like, in the middle of an inner tube. So, the deal is that you can use this to spin the superfluid in a bucket if you wanted to. You just have to make it so that is spun in a way that there was kind of a hole down straight through the middle of the bucket.

Kelly: Okay, alright. I'm not clear on how you would do that but I understand the principle I suppose.

Fiona: Like when you drain the water out of your tub you know and you have this little, sort of, channel in the middle going down, you know, this vortex and there's no water in the vortex.

Kelly: Okay.

Fiona: And it's sort of like that so you know the superfluid is whirling around this hollow tube and in the middle there's still helium there but it's not superfluid helium, it's ordinary liquid helium.

Kelly: Okay.

Fiona: And this is called a vortex. And so if it, if you start spinning the bucket too fast then it needs to start turning. It will do that by making these vortices rather than having the rest of the fluid start to spin with the buckets.

Fiona: I don't know how much of your high school science you remember Kelly, you may or may not...

Kelly: I'm sad to say I don't remember much.

Fiona: Yeah. Do you remember anything about atoms? Do you remember pictures with dots in the middle and circles around them that were supposed to represent atoms?

Kelly: And metals, metals and things, yes I, yes.

Fiona: Right

Kelly: I don't know that I remember anything useful but I do remember them.

Fiona: So you know you have this picture of the dot in the middle that is kind of the nucleus and then there are these circles around this nucleus that are supposed to represent, you know, where the electrons that orbit the nucleus can live.

Kelly: Okay.

[26:14]

Fiona: The reason that these pictures are useful is that when people first started thinking about atoms and there was this kind of question, well, you know, why does the electron not just fall in to the center of the atom. You would expect that the electron would sort of slow down, loose some energy as it's spinning around and that it would just fall in. And it turns out that the way to understand this is, you draw this picture with the dots and the circle and then you pretend that the electron itself is not like a dot, it's not like a little particle, it's like a wave. So you have to basically make a wave along this piece of string. So you can draw a little wave along your circle but now you have to be careful because you have to draw this wave in such a way that once you've gone all the way around the circle if you started out again, right, in other words like if you take a piece of string and you hold it at both ends and you pluck it in the middle and you watch these patterns of vibration, right, the end points, you know, are both at the same place if you like, and you can count the number of, kind of, waves along the string.

Kelly: Okay.

Fiona: An electron around a nucleus, this is sort of the first picture that people had of how to understand how that works and how the electron can't fall in. So what's special about this picture is that you have to think about the electron not as behaving like a little ball but it's behaving like a wave in a piece of string and that sort of one of the fundamental things about quantum mechanics. So, the thing about the superfluid is that it's exactly like a single electron in this sense. You can think of it as one giant wave and when you make it turn around something this wave has to have some number of undulations in it.

Ben: Right, so, an electron is a quantum mechanical particle and I'm sure you've heard that quantum mechanical particles are both particles like billiard balls and they're also waves, whatever that means. And the fundamental feature of a wave is that it's got something called a wavelength. So, if you move some fixed distance along it you'll see whatever this pattern is repeating itself. All that matters is that this pattern repeats itself after a fixed distance. So I want you imagine that your electron is like a belt. This belt has holes in it every, say, one inch. Okay, very inch there's a hole in it along this one long strip of leather. And so when we want to put an electron around an atom that's like saying okay, we have this belt and we want to wrap this belt around this nucleus. But, the constraint is that when you do it you want to make it so that all of the holes of this belt line up so that when you wrap the belt around a second time all of holes in this belt poke through. So imagine that you have this nail and you're trying to put on this belt by pushing a nail out through one hole and then another hole.

Kelly: Okay, yeah.

Ben: And so, because of the spacing of these holes, in essence, because of this fixed wavelength, characteristic the electron, you can only end up with a very well defined set of different belt lengths, right. You can make it so the belt loop goes around and two holes are matched up and then you can put it so that the first hole goes around the next hole and expands the width of the belt. Okay, yeah, so in essence, that's all that's going on quantum mechanically. These things have waves associated with how they move and because we want these waves to line up consistently because we want the holes in the belt to line up consistently, it means that we're not free to make this belt ring an arbitrary length.

Jocelyn: So, it can't be a belt for ants.

Ben: Yeah, it can't be a belt for ants. You can't make the belt arbitrarily small because you need these holes to line up. The smallest ring of belt you can make is putting a hole through two adjacent nails, right.

Kelly: Right.

Ben: So, in essence this is why the electron doesn't fall into the nucleus of the atom and it's also kind of a description of why you, why vortices have to form. In essence it means that you can't get a fluid flow in a ring that's narrower than some radius.

Kelly: Say, that one more time. You can't get...

Ben: You can't make it so that this quantum fluid flows in a circle. In essence that's what we're talking about. We want, you know, if you had a bucket of water and you spun it you could just imagine that if you looked at a point on it, all of the fluid would be tracing a circle across the top but because this is a quantum liquid it means that if we had a bucket and had set it to spinning there'd be some radius.

Kelly: So, what you're saying is that the rate of spin is like the distance between the holes in the belt and it's not arbitrary, it's set.

Fiona: Yeah.

Ben: That's right, you got it. Okay, congratulations. You're a quantum mechanic.

Laughter.

Jocelyn: You get space superfluids in neutron stars.

Kelly: Okay.

Jocelyn: And those are actually very hot but the thing that happens is that when you make matter very, very dense, so, a neutron star is like the collapsed remnant after a super nova, it's very, very, very, dense. And then just the scale at which things happen is a lot more dramatic. So, by our earth standards it's very hot, but by the standards of neutron star matter it's very cold and so you have a transition of a fluid of neutrons in the neutron star to a superfluid shortly after the supernova forms the neutron star.

[31:19]

Kelly: Okay, and then, does that have any observable effect? I mean, are there things about the neutron stars that people look at and say well, this is the result of the super cooled fluid?

Jocelyn: Well, yes, yes there are. One of the easiest things to explain in terms of what you see with neutron stars has to do with this spinning. So, what happens is neutron stars are some of the most perfect clocks in the universe. They spin at a very regular rate and we see radio pulses from them at an exceedingly regular period. Except some of these newborn neutron stars will glitch and so usually they spin down slowly so their period of rotation is slowly increasing as they settle down but a few of them suddenly start spinning faster again and then settle down again and this is really weird because the radio signals aren't changing in character. Like, it's not some electromagnetic thing that's changing but it's just sitting there alone, why on earth could it start spinning faster all of the sudden? And the most common explanation and there are still, you know, lots of uncertainties and details, is that what happens is, this superfluid is a bit decoupled from the rest of the star. So, the crust of the star with this field that is sending out this pulse is slowing down because the energy is going into the magnetic field and powering the glow of a nebula around it. So, that's what's causing it to slow down. But then the superfluid doesn't really see this except it's connected to the crust and the magnetic field through the vortices.

Kelly: Okay.

Jocelyn: And so eventually there's a stress that comes in because the fluid is spinning at its nice perfect superfluid rate except its container the crust has changed its rate and this causes sort of tension in the way these vortices going through the superfluid connect to the crust and you have this sort of massive reconfiguration event where some of the energy from this superfluid core is transferred into the crust which gives it that spin-up and then it settles down again. So there's a few things you observe neutron stars doing that seem to require a superfluid to explain and of course you can also do the prediction of how the matter in a neutron star behaves and it says, oh look we probably get this superfluid transition, mathematically at this temperature and so you have a consistency there which is kind of neat.

Ben: Alright, that was great. Thank you Jocelyn, thank you Fiona. You have pleased me. Your efforts have born fruit and that fruit is sweet. Here's some fruit. You guys both get super fruits. Fiona, you get a blueberry.

Fiona: Nom, nom, nom. It's delicious. Thank you.

Ben: Nice. And Jocelyn you get an acai berry. That's a superfood right?

Jocelyn: I've never had one. That's very exciting. Yes, that's a superfood, thank you Ben. Nom, nom, nom.

Ben: Alright, I'd like to thank my guest, Kelly Link, thanks Kelly! I hope you had fun.

Kelly: I did! Thanks you guys so much, that was really interesting.

Ben: Sweet. Alright.

So, listeners, you you can email us if you'd like to at barn@titaniumphysics.com or you can follow us on Twitter at @titaniumphysics or visit our website at www.titaniumphysics.com or you can 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.

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[36:24]

Ben: Um, so let's start talking about this superfluid. Let's go through the attributes of a superfluid before, because, I mean, it's like talking about some type of potato nobody has seen before. If you haven't seen the potato at least a good description is required before we are talking about why the potato is that way.

Kelly: Isn't one potato pretty much the same as the next? I don't know what you've been eating in... I guess they don't have very many cod these days.

Fiona: I was imagining a super potato of some kind.

Ben: Yeah.

Jocelyn: That's the point though, we're all familiar with regular liquids so, you know, regular fluid, so if we have a superfluid we need to understand what that means. So, similarly, if we had a super potato.

Ben: Yeah.

Kelly: Yes Ben, what is a super potato?

Ben: So, let's start talking about superfluids by comparing and contrasting...

Jocelyn: Actually I'm interested in the super potato question.

Ben: I, that's the Titanium Agriculturalists podcast and ah, I can try to get you on that on but...

Kelly: I'm actually a little afraid of the super potato. It sounds dangerous.

Ben: Well, apparently

Kelly: Less useful, more dangerous.

Jocelyn: Is that like all the potatos moves as one?

Ben: Well, the potato always does that, right?

Kelly: I guess.

Jocelyn: You just need to put it near your mouth and it creeps in and down your throat.

Ben: Alright. Let's not give the game away.

[37:51]

Kelly: So, can we extend this a little bit more. What if you're not in a canoe, what if you're in lake of super fluid that is, you know, say you're 5'7" and the superfluid lake is 9 feet deep, are you going to drown because you can't swim, would you sink?

Jocelyn: I guess if you're less dense than the superfluid.

Kelly: Okay. Yeah, I guess it would depend on what the superfluid was made of.

Jocelyn: I mean there are certain practical issues in that most actual superfluids are near absolute zero.

Fiona: You would freeze to death before you drown.

Ben: Luckily you would freeze to death before you drown.

Kelly: Alright.

Ben: But yeah, I think that' slight. I don't think you could, if you can't paddle a canoe in it then you can't swim in it.

Jocelyn: If you would, I mean...

Fiona: Well, the point is, you, you, you either float which you wouldn't if it were helium or you fall straight to the bottom very quickly, right. For the same reason. If it's going to let you through it's just going to let you through.

Kelly: And if you were floating you'd have no way of getting off that surface anyway. You would be stuck there.

Ben: Right.

Kelly: Unless somebody threw you a rope.

Jocelyn: You would have to try to splash around and you wouldn't get anywhere.

Ben: Maybe if you threw your shoe in the direction opposite where you were trying to go.

Jocelyn: Actually a shoe might be enough because once you get going there's nothing that's going to stop you.

Ben: That's right, but I mean...

Jocelyn: You've got the little layer of superfluid against your skin but that's just, you know, you're, you know, you're greased through the rest of the...

Kelly: Sure, okay.

[39:15]

Kelly: When I was a kid I went to a Christian summer camp in which one of the activities was, they put a bunch of us in a corral with a greased piglet and the goal was to catch and hold on to the greased piglet.

Ben: Right.

Kelly: It was a lot of fun.

Fiona: Very hard to...

Kelly: I actually did. I grabbed hold.

Jocelyn: You won the piglet contest.

Kelly: I did. I won the greased pig catching and holding contest.

Ben: Is the trick to grab it by the mouth.

Kelly: What I did was to make myself a ball around it.

Ben: Ahhh, that would work.

Jocelyn: Sort of tackle the...

Kelly: Yeah, I did, I tackled the pig. I haven't thought of that for a long time.

Jocelyn: I guess that's what you need to do to hold on to superfluid. You know, you just have to sort of surround it. You can't....

Ben: Well, you can scoop it, you can't paddle it. You can't, you couldn't...

Jocelyn: You can't grab any. Well, I guess you can't grab water either. But more so with superfluid.

Kelly: Moreso, okay.

Laughter.

[40:25]

Jocelyn: So, that's what actually, oh, go ahead.

Kelly: No, I was just going to say, I mean, it sounds like it's something that is easy to observe on a large scale. Like that you can, without a lot of resources, you can, it also sounds like it...

Jocelyn: Well you do have...

Kelly: Has practical applications.

Fiona: Well you do have to be able to get it cold enough.

Kelly: How cold?

Ben: Yeah.

Fiona: Sort of -271° C, approximately which, um, is not something that you can do with out fairly specialized, without reasonably specialized equipment.

[41:10]

Fiona: Well I thought that the, um, analogy of introversion versus extroversion that Kelly brought in earlier is useful. So, a fermion, or like, you know, an electron maybe if you want to talk about electrons. A fermion is the extreme of a very, very introverted particle. It wants to be alone and basically if there's anybody else in the same room it can't live with that at all and it's ...

Kelly: So, it's like Greta Garbo.

Fiona: Right.

Kelly: It's a Greta Garbo. Okay. Alright.

Fiona: Basically it's gotta be kinda by itself in its own little box.

Kelly: Okay.

Fiona: Um, now, and then bosons are the opposite extreme. So, actually, you know you can put as many bosons into a Volkswagen Bug as you want. There's no limits.

Jocelyn: Millions.

Fiona: And so these are the two kind of fundamental, different entities that exist in nature. And the truly surprising thing is that actually, if you take two fermions to, you know, they're each in their own little box, but maybe there's a telephone and they sort of talk to each other in a certain way but this sort of collective of these two fermions that are talking to each other kind of start to behave like bosons. They don't have a good social...

Jocelyn: You coupled to another person by friending them on Facebook and then all of the sudden even though you are an introvert you find yourself surrounded by other people.

Kelly: By friends.

[42:26]

Jocelyn: The lesson of these of these movies though is that humans, for good or evil, are individualistic fermions that just like run into each other all the time.

Ben: Right. And create...

Jocelyn: That's what science fiction has told me.

Ben: Good drama. Okay, so zombies are like bosons and survivors are like fermions.

Kelly: Okay, alright.

Ben: You can't... Right, you can't put two jocks in the same shopping mall or, you know, one gets kicked out. You can have one of each type of personality in the shopping mall whereas with zombies you can put as many zombies in a shopping mall as you want.

Laughter.

Kelly: As long as you're not in the shopping mall yourself. Sure.

Ben: Right. Well. We're talking about very cold places.

Kelly: Very cold shopping malls, alright.

Jocelyn: Well, I mean, because like the reason we don't see, you know, just, just, well, we don't always see stuff behaving in this quantum way it's usually because of thermal stuff kicking it around and messing up the states. It's only when it gets very cold that they can all kind of settle down into their quantum states that they like and if it's a bose particle they all collapse down to the lowest possible state because, you know, they're lazy. And then they just sit there all together, happily. Whereas the fermions, you know the fermions, the first fermion to get to the lowest state is all dibs and then the rest of the fermions have to find the next best thing.

Kelly: A little bit like a New York subway car where everybody sits at a certain distance from each other.

Ben: So...

Jocelyn: Unless they were ghosts then they could all sit in each other's laps.

Ben: That's right. You could get all of the ghosts sitting in one car, in one seat.

Kelly: You all are making ghosts sound very, very friendly which is not usually the way I think of them but...

Fiona: They're not gregarious.

Kelly: Well who knows, maybe they are.

Jocelyn: Well, just think about the, you know, over the time of the earth the number of ghosts is already, is always going to be increasing so they're just the density of ghosts is going to keep going higher and higher and higher so they better be able to get along.

Kelly: Well I do think about that occasionally. It is a troubling thought you know, not that your building is haunted by one ghost, but probably haunted, your area of terrestrial space is, you know, probably a lot of ghosts bumping around in that area.

Ben: Lots of ghost bugs. Weevil ghosts walking all over you.

Jocelyn: And more things have died in the place that your sitting than, than...

Laughter.

Kelly: I hope not literally.

Laughter.

Jocelyn: Well, go back over the history of the earth...

Fiona: How old is your furniture.

Kelly: Well, this couch is a very old couch so maybe...

Laughter

Jocelyn: Many bedbugs have died.

Kelly: I hope so.

Laughter

Jocelyn: But you know, like dust mites.

Kelly: Yeah, I think once you start thinking about dust mites, absolutely, okay. Alright.

Jocelyn: Your house is just totally packed with dust mites.

Fiona: But they're not very big.

Fiona: Um, so, we've, I can't stay too, too long Ben because it's, I have to get up fairly early in the morning. Maybe we could keep...

Ben: Let's start moving forward.

[45:31]

Ben: So, Fiona brought up the fact that, you know, if you want to stir soup you essentially take a spoon and you whirl it around. But, just as if you wanted to paddle a canoe in superfluid you wouldn't be able to. You can't really stir the superfluid if you move at a reasonable speed your spoon in the big bowl of superfluid would just kind of pass around the spoon and you won't be able to get a good stir in.

Kelly: Yup.
Ben: Actually, there are videos online of propellers in superfluids and they start to breakdown eventually at a fairly low rate of speed when you try to spin the propeller it won't cause the fluid to turn.

Kelly: Okay.

[46:10]

Ben: Maybe if you...

Kelly: No, I, I get it, I mean I see that one of the uses here, of this is, is a theory is that it explains behavior of stuff we can't observe up close but you know, I'm also, it sounds like there are practical applications as well or that there potentially are practical applications.

Ben: So, one of the limitations we've mentioned before is that it, you know, you need to cool a liquid down to slightly cooler than outer space is. You need a ridiculous amount of machinery to get the stuff and so that limits...

Kelly: Practicality.

Ben: Practicality. It's cool stuff.

Kelly: It's fun but not practical, that's what you're saying.

Jocelyn: Well, the same kind of physics that explains superfluidity will also explain superconductivity.

Kelly: Sure.

Jocelyn: When it's a superfluid of electrons.

Kelly: Okay.

Jocelyn: And that's gonna have more, super, superconductors have, sort of more, easily envisioned applications.

Kelly: Okay.

Fiona: I was thinking, just want to interject that a superconductor is something that conducts current without basically dissipating any heat or energy so current with no resistance basically. So you can see this could be a very, um, exciting thing if you could make it work at temperatures where you could really, design devices. Well, I think one of the big problems with these things in general is they happen when systems are very, very, very cold and so if you actually want a gadget that you can carry with you that's not very practical since, typically, to make something that cold you need a fairly large and bulky apparatus.

Jocelyn: Although for superconductors there's that, there's some crazy high speed, super long distance train where you have...

Fiona: Oh the train, yeah. The maglev.

Jocelyn: Train, yeah. You magnetically levitate a train and you can sort of preserve you know, you spend a lot of energy cooling stuff down to this super, super conducting temperatures but then once you're there you just have to insulate it. And then you can, you can just shoot people at super high speeds without the resistance getting in the way.

Kelly: Right.

Jocelyn: So, that sort of, you know this whole lack of viscosity and lack of resistance has potentially interesting implications if you can, if you can sort of access this with some...

Kelly: Sure.

Fiona: If you can create the conditions that will, that it requires.

Kelly: This is why fiction is cheesier.

Fiona: Not for us.

Laughter.

Ben: That's true