Episode 67: A Phonon Call
Physicists: Fiona Burnell, Darren Peets

Transcribed by Denny Henke

Ben: Never be afraid. There's nothing which is known which can't be understood. And there's nothing which is understood which can't be explained. For over fifty 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 is understandable ways and I've bestowed upon these women and men the title of Titanium Physicist. You're listening to the Titanium Physicist Podcast and I'm Ben Tippett, and now allez physique!

[1:51]

Ben: One thing I find fascinating is how an assembly of one type of thing can cooperate to unwittingly act like another type of thing. We're not unfamiliar with examples of this. There's something called the Zeitgeist for instance, the literal ghost of an era, where the public mood is palatable and coherent in some kind of weird way. Instead of just millions of disparate opinions everybody's kind of thinking the same thing. Where does that come from? Like how everybody all of the sudden started growing beards. Where did that come from? Like, in the last ten years, suddenly everybody's wearing beards. No one in particular told us that beards were cool looking it's just that everybody kinda changed their minds on the topic, all of the sudden. And this type of thing happens a lot in physics. For example, an individual water molecule is just a particle. It bounces off all of the particles surrounding it and that's its life but if you have enough of these molecules you get a fluid, a river. Waves travel across the top of it. It flows, it eddies and curls, it sticks to things, it carves canyons. It has all these macroscopic qualities that don't have any apparent cause at the scale of an individual water molecule. Or consider metals. You've got individual atoms, each shares valence electrons with it's nearby neighbors to form a rigid structure and then suddenly at the macroscopic scale electric currents flow it, just like water through a pipe. What capacity of the individual atoms is it that allows the distinct behaviors to show up at the large scales? Now, you might be unconvinced. You might be like well those are both examples of particles acting together to make something that acts like a fluid, big deal. Crowds of people act like fluid. Well, there are also examples where the opposite is true, where you've got large scales cooperation of tiny little things that generate what we recognize at the large scale to be a particle and I don't atoms in a baseball. I mean, when you study the thing you say there's a particle but then when you look at it there's no particle in there, it's just macroscopic behavior. We call those quasi particles. It's absolutely bananas. Anyway, my favorite example is called a phonon where sound waves traveling through a crystal act just like particles. Anyway, that's today's topic.

So, speaking of things that are made of particles Anthony and Megan Leon are software developers and they live in Hawaii and they're also made of particles. Hello Anthony and Megan!

Anthony: Hi.

Megan: Hello

Ben: Alright Anthony, alright Megan, for you I've got some magnificent physicists. Arise Dr. Fiona Burnell.

Fiona: Boink!

Ben: Dr. Fiona did her undergraduate degree at UBC and here PhD at Princeton. She's now faculty in the physics department at the University of Minnesota where she's a specialist in condensed matter. And arise Dr. Darren Peets! Dr. Darren did his PhD and UBC and he's currently Xide fellow at Fudan University's Advanced Materials Laboratory in Shanghai China where he studies magnetic materials and super conductivity.

Okay everybody, let's talk about phonons!

Fiona: So, what I love about phonons is that they capture two of the most fundamental aspects of what we have to think about when we study materials. Um, which is they tell us that we need to think about both the interactions between particles and the material, in this case between the atoms themselves and we also need to think about quantum mechanics. And in fact phonons were sort of one of the first examples where people really understood that these were both essential in understanding physics of materials. So, so back in the late 1800's, one of the few experiments that people could do on crystals at the time is they could measure what's called their heat capacity. So, you know, basically, what happens when you heat something up is that you're putting energy into it. And, so, what they could do is essentially measure how much energy you would need to put in to a given material to change it's temperature by say 1°. So, this was something that, you know, people could do without the sophisticated laboratory equipment that we have today. So, in the late 1800s, before people sort of really understood very much about quantum mechanics, most of the pictures people had in their heads of things were, were classical. And these classical models of the, of the you know, the heat capacity of a crystal, which we'll talk about in a moment, basically predict that the heat capacity should be essentially independent of temperature. And what happened was that as people started to be able to do these experiments at lower temperatures, they were able to notice that that was in fact not true in real solids.

Ben: Okay, so, before we go any further, Megan and Anthony, are you familiar with the heat capacity as a physical thingy?

Anthony: Ah, not really, no.

Megan: No.

[6:37]

Ben: Okay. So, the moral of the story is, different materials require different amounts of energy to heat them up by 1°. So, some things, like aluminum, heat up with very little energy, right? It doesn't take much heat to get your piece of aluminum to room temperature and other things take a ton. Like, ah, water is notorious for having a huge heat capacity. There's two ways to think about it. Either it takes an enormous amount of energy to heat water up 1° or alternatively, if you heat water up to a certain temperature it has tons of energy and so it's temperature will come back to room temperature very, very slowly because so much energy is stored in that.

Anthony: Oh, okay, that makes sense.

Megan: Yeah.

Ben: So, what they were doing is they were taking crystals and they were like, what do we know about crystals? I don't know, let's make models of it and their conclusions, based only on classical physics and what they knew about thermodynamics at the time suggested that the heat capacity would be constant, that it wouldn't be dependent on temperature. And what Fiona said was as they did experiments on crystals, on metals, you know, they found that the lower the temperature got, the less heat capacity the system had.

Megan: Huh.

Anthony: Okay.

Ben: Actually, the question was, why does it act like that? Why does it act in this particular way?

Anthony: Right.

Ben: And this was a turn of the century problem, right? 1907, Einstein put his two cents in, that type of era, right? So, right on the cusp of people needing to insert quantum mechanics and the idea of quantum mechanics into their experimental physics.

Anthony: Okay.

Ben: So, heat capacity is a, it's an interesting thing because it's kind of like asking somebody, ahhhhh, well let's say there's a person with pockets and you're going to hand him oranges and he puts one orange into each pocket. And you're asking, how many oranges do I have to give him before the number of oranges in his hand increases by one? So, different people have different numbers of pockets, I've got four pockets which means that you have to give me five oranges before I have to store one in my hand, right?

Anthony: Right.

Megan: Right.

Ben: You have eight pockets and so somebody has to give you nine oranges before you have to store one in your hand. You dig?

Anthony: Yeah.

Megan: Yeah.

Ben: So, ah, particles are kind of like that. A particle can store energy in a variety of different ways.

Darren: Your oranges are heat in this case, by the way.

Ben: Yeah, yeah, yeah. To give the end of my awesome analogy away, the oranges are heat in this case. So a particle can store heat energy in a variety of ways. You can cause it to vibrate, ah, left to right, you could cause it to spin a little bit faster, you can cause it to bounce back and forth or you can cause it to bounce up and down.

Megan: Right.

Ben: So, the different ways, so, the deal is that ah, if you, if you give a particle a little pack of energy it will store it in one of those ways and overall each time you give it another little packet of energy it's going to store it in another way until, you know, overall it has to bounce back and forth a little bit faster. And so, the moral of the story is, depending on, we call these degrees of freedom, it can vibrate up and down or left and right or back and forward or wiggle in some certain way. And so if you're dealing with a molecule, the more degrees of freedom it has the more different ways it can store energy and the more energy its going to take to increase the temperature of the material. Because it can hide a little bit of energy in vibrational energy or it can hide a little bit more energy in spinning energy. And it doesn't have to devote that energy into vibrating around temperature energy. Does that make sense?

Megan: Yeah.

Anthony: Yeah.

Ben: So, the question is, where is the energy going? How is the, how is the system storing energy, in what way is it storing energy so that you get this particular type of heat capacity, this particular temperature dependence in the heat capacity.

Anthony: So, there's multiple ways for the molecule to store energy and then once you have achieved all of those ways, like you've stored energy in all those different ways, then it increases temperature?

Ben: Yeah, by a little bit. Right?

Anthony: By a little bit.

Ben: Yeah.

Anthony: What's, what is the temperature in that analogy? Like...

Ben: The temperature is when the particle bounces back and forth against other things.

Anthony: Oh, okay. Okay, I get it.

Ben: Okay? So, um, it won't manifest as a temperature difference until the energy you give it makes it bounce back and forth. And so it's kinda like the difference between, you know, if you take like a basketball and you throw it against a wall, the basketball is a very simple object. In the basketball all the, most of the energy you give it in throwing into it will manifest as motional energy. Whereas if you take like, um, a lamp, like one of those IKEA lamps that's covered in springs, and you throw it against the wall, some of the energy when it hits the wall will bounce back and you'll get it moving again but a lot of the energy will be dissipated into causing the lamp to vibrate and deform itself and stuff like that.

Darren: In both cases where it's actually in contact with the wall it's deformed.

Ben: Yes, that's right. At that moment.

Darren: In one case you get the original form back when you're done.

[11:37]

Ben: Yeah, because it's a simple system and there's not very many different ways it can hold the energy internally, right? And so the complexity of the system and how it can store energy internally determines how much heat capacity there is in the system. Does that make sense?

Anthony: Yeah, it does. So, what makes a water molecule so complicated, so that it has such a high degree of this?

Darren: The hydrogens, the hydrogens are actually shared between two adjacent oxygens and then they choose one to be closer to at any given time so they can move back and forth. Ah, but of course if one, if one moves away then one of the other ones has to move toward that oxygen so there are always two that are close.

Anthony: Okay.

Megan: Okay.

Darren: You also have the ability for the thing to flap back its wings, basically. Like this, this angle is supposed to be a 104° or whatever but it doesn't have to be exactly that all the time, it can vibrate a bit.

Ben: The wings in this case are the hydrogen atoms bonded to the oxygen one. So it can, yeah, so it's just super jiggly.

Megan: Okay.

Anthony: Okay.

Ben: Alright, ah, so, Fiona, where were we?

Fiona: I think the basic overview, and maybe we'll talk about the different models, in detail, is that so, okay, so people are thinking about the heat capacity of crystals and as Ben was explaining, so basically in order to understand heat capacity you have to think about what, if you like, particles or modes or you know, what's going on to kind of store the energy in the system. And the earliest model of this was Ludwig Boltzmann in the 1890s. And he sort of said, so, you know, so, you think about the atoms in your crystal as being sort of, ah, balls, if you like, attached with springs. And you really think about, you know, just balls and springs in a kind of classical sense, you get the correct answer at high temperature but in fact something which was very clearly not consistent with experiments as they got to lower temperatures. So, there were a couple modifications of this, basically Einstein was the first person to introduce quantum mechanics into the theory of vibrations of atoms in solids. And he had a model which sort of qualitatively, in some sense, got the right behavior of temperature but it was, but it was wrong, in a sense in a quantitative way. Depending on what you mean by quantitative or qualitative. He predicted the wrong mathematical function for how it behaves with temperature but he...

Anthony: It was like the wrong math but got it right in the solution?

Fiona: Well, what his model got right is the fact that if you look at this heat capacity it basically goes to zero, um, for most solids as you decrease the temperature. But, he actually had the wrong prediction for how it gets there. So, he had quantum mechanics but in fact he didn't include any interactions with any atoms and then the third kind of modification was due to Debye who introduced, as well as quantum mechanics, included interactions between the atoms and the crystal. And when you do that you get, essentially, a very good fit to the experimental data. So that's kind of the, I guess, if you like, it's a historical picture, but this was, you know, really one of the first indications that quantum mechanics was a fundamental part of understanding elementary properties of solids like, how they absorb energy, essentially.

Anthony: So the heat capacity, you said, it goes down the less energy you give it.

Darren: When you cool it.

Fiona: Okay, so, at lower temperatures, as Ben was saying, there's, you know, if you put energy into any system there are a number of different, sort of, ways that the energy can be stored. Imagine just a room full of bouncy balls, you know, so that's kind of like a gas. So then you put some energy into that and basically what's happening is, you know, it's going to be kind of random. So, some of the balls are moving very fast, some of them are moving slowly. Basically, at lower temperature they are going to be a lot less balls that are moving very quickly. And so what that corresponds to in terms of thinking about kind of modes of different energies is it means that you can have you know, a molecule that has different modes, maybe it has vibrational modes and rotational modes and yeah, or if you think about these atoms that coupled in the solids, some of the, you know, modes have higher energy than others and so what happens is as the temperature goes down you have a lot less of those high energy modes going on and a lot more of the low energy ones. It turns out that that means that basically as you go towards zero temperature, the energy starts to be more and more independent of temperature.

Anthony: Okay.

Darren: If you're trying to store energy in the system, at low temperatures, a lot of the places where you would try to store energy just aren't available. You would require too much energy to actually put something in there and at low temperatures you don't have that. Everything is cold.

Anthony: Okay, so in the classical sense they were thinking that no matter how low you got the temperature, the heat capacity would be the same but as it turns out it's not because there is less places to put the energy?

[16:44]

Fiona: Correct. Yeah, so it's sort of a quantum mechanical affect.

Anthony: Ah, that's interesting.

Fiona: Yeah.

Ben: It's like you've got the coat pocket analogy where there's a person giving oranges to, the colder they get the more pockets they zip shut and then so the amount of energy it takes to change the temperature changes.

Anthony: Okay.

Ben: Does that make sense?

Anthony: So, like the heat capacity goes down to zero the closer you get to, I would assume, absolute zero and so the amount of energy you have to put into the solid is very low in order to get an increase by 1° and then it just continues to increase as you increase the temperature.

Ben: Yeah. Because as it warms up...

Anthony: There's more places, there's more pockets...

Ben: It releases, yeah, it releases more internal ways the system can hold energy.

Anthony: Oh, okay, cool.

Ben: So, before we start talking about phonons specifically, what they are, let's start talking about these different solutions.

Darren: Your solid, you've got all these atoms, they're in some sort of set arrangement in space. So, the first thing to think about the simplest model would be each atom as a ball and then they have interactions with the atoms around them, so those are springs. So, if I have these atoms on some sort of a grid in three dimensions and I say okay, all of these are in fixed in position and then I look at one somewhere in the middle, well I can move it up and down or left and right or toward me and away from me. And if I take it out of the center position it's going to have one spring pushing and then one spring pulling to bring it back to the center. And I can give it a kick, you know I kick it to the left and it moves to the right and then it bounces back and forth for awhile. I can have the thing vibrate up and down, toward me or away from me. Or I can do something that's a combination of them, like I can pull it diagonally and it will run around and I, back and forth diagonally. So, those are the basic modes that are available for it on that one site. But, the other things are not fixed, they can vibrate as well. So what ends up happening, you can imagine I take this atom and I push it and I, you know, I really push it away from myself kind of hard and everything around it goes with it. And, so this travels and this is, essentially, a sound wave. And if I wiggle it left and right, everything will wiggle left and right as well and this actually looks more like light. It travels away from me but the displacements, the way that things are moving are not away from me they are just left and right. And I can do that up and down as well. So the one where I push it is called an acoustic mode because it's similar to sound. The one where I wiggle it left or right, up or down, those are optical modes and there's two of them. And this is a collective wave thing in the crystal.

Anthony: So, up and down and left and right are optical and pushing toward or away from you is like a sound, acoustic, why are those differentiated?

Darren: So, photons, light, only have two of the three for instance. But phonons have all three. The only real difference is that the direction that it's traveling is the same direction as the things are moving individually. It does make a difference in what the energy is as a function of the momentum of the material, or the momentum of this wave.

Anthony and Megan: Okay.

Fiona: I think one of the reasons for the nomenclature is, so there's the acoustic modes are ones that, you know, basically as the wave moves slowly it carries very little energy. So this kind of relationship between the speed and the energy is what you would expect for water or something like that. An ordinary wave and that you know that relationship actually defines how quickly sound propagates in your solid and stuff like that. The optical modes, one of the reasons that they are called optical modes, if you actually shine like a laser or something onto your system and your system absorbs photons from that laser, the photons can excite these optical modes sometimes. But they can never excite the acoustic mode.

Anthony: Oh. That's interesting. So why the photon wouldn't be able to push the system in a particular way.

Fiona: It has to do with the energy. So, well, okay, so it has to do with the relationship of the energy of the photon and it's momentum. So, when a photon comes in it transfers both energy and some momentum. And basically um, a photon of a given momentum always transfers a relatively large amount of energy. So, you can have a phonon which has a small momentum and like a very small energy but basically the photon assumes it has a momentum that is not tiny, it has, basically the speed of light is so big it's going transfer a significant amount of energy and so that's why it can't access these modes which have low energy when they are low momentum.

Anthony: Oh, okay, so it just doesn't interact because they don't accept that type of energy, that high amount of energy.

[21:47]

Fiona: Yeah, exactly, it would have to, yeah, that's right.

Anthony: So ah, have we defined what a phonon is?

Darren: So, we've got a wave traveling through the material and we've got three different types of waves that can travel though the material. Two types that are optical and one that is acoustic.

Anthony: Right.

Darren: If you have a wave you can also have a particle. Because it's a wave it's a particle. This is what quantum mechanics will tell you.

Ben: Wave particle duality.

Anthony: Right. You said that sort of like ah, axiomatically, like its, like if there's a wave there can be a particle but like in the ocean, like there's a big wave there but you don't normally see an ocean particle, like, spring out of that. So, what is a phonon in that context? How would you represent it as a particle?

Fiona: So, I think it's helpful to be precise about what you want to mean by particle. So, when we say particle, I think that invokes this idea of something like an electron or

Anthony: Yeah, like a ball or electron or just something...

Fiona: Yeah, something that you can microscopically kinda look at and say, oh, it's this point thing. No matter what scale you look at basically it's a point object. And so one of the things that Ben touched on in his introduction is that when we say in materials there are sort of particles and then there are what we often call quasiparticles which are things which behave like particles in the sense that they have a well defined, you know, energy and velocity and, I mean, they can scatter off each other but you know basically there are well defined excitations from long periods of time. And so if you think about your model of balls and springs or, like my favorite, imagine that you have a slinky or a string or something like that and you start shaking your slinky, right, and so you know that if you push the slinky you see this wave go traveling down it and that wave is carrying a fixed amount of energy and it's traveling at a particular speed. You know, and it has some shape, you know kind of propagates along. And this shape doesn't really change as it moves. And so that wave is really what we mean when we say, you know, a quasi particle. That wave is your classical analog of a phonon propagating along carrying some energy.

Anthony: Oh, okay. So, it's, it's like the representation of the wave, like the, like the aspects of the wave that are going through the slinky.

Megan: Like the effects but it's not an actual particle.

Fiona: Yeah, yeah.

Megan: But it's not real...

Anthony: It's not like an electron or

Fiona: If you zoomed in you would just see slinky everywhere, you know, microscopically it's all made of slinky but there is this excitation, you know. You put in some energy and it propagates at a speed.

Anthony and Megan: Okay.

Fiona: So that's like the right image to have in your mind when you want to think about a phonon as a particle.

Ben: ... not be convincing to you that phonons are particles at this point in the game. Because you're like, well yeah, then isn't anything a particle and your like... So, before we go on, let's go back to that heat capacity thing. Not because its particularly useful in talking about phonons or imagining what they are but because, you know, for me, it kind of put the stamp of particle on the thing. So, earlier when we were talking about heat capacity we were saying that the issue here is, where is the energy stored? How is the energy stored? Can we name all the ways that the energy is stored in a system? Right?

Megan: Right.

Ben: So, Darren was saying when you describe a crystal as a bunch of particles that are kind of locked into fixed places in a lattice where there's an atom at the center and he has an atom above him and an atom below him and an atom to each side and he's kind of pushing on them and they are kind of holding him in place. I guess it's a he now?

Laughter.

Ben: The earliest methods for describing how energy was stored in the system, imagined each individual atom as being held in place by the ones around it, okay? They say, where's the energy stored? Well, the energy is stored in the atom wiggling back and forth in place.

Anthony: Okay.

Megan: Yeah.

Ben: And so, its like, they can wiggle a lot, or it can wiggle a little bit and it can wiggle in three dimensions. It can go up down, side to side, etc, right? And the problem with that model, as they said, is it doesn't correctly predict, as the temperature decreases, how it's going to change what the heat capacity is.

Fiona: So, basically the kind of cartoon picture that we have in our mind, of a solid, is, I take a bunch of beads, you know, I bind them together with springs, okay and I have this bead spring thing. It kind of looks like a big trampoline. So, you know, if you build this in your basement this would be a classical system. Obviously it's, you know, it's big enough for you to touch, quantum mechanics is not important, and that was kind of the first model. This was the Boltzmann model, the first model that people had.

[26:31]

Um, and so you know, you would look at your network which I guess a trampoline is two dimensional so I maybe you build a three dimensional one, right. And you basically say, okay, how many, you know, ways can each atom wiggle and the answer is, you know, basically it has three directions it can wiggle in. And so that basically, um, corresponds to that constant heat capacity with temperature. Now, the reason that that's not correct is when you actually think about these phonons, which are kind of the particles carrying the energy. In that treatment those phonons are classical particles and in reality in a solid, phonons are actually, you know, quantum mechanical particles. Um, and that actually affects, if you like, how many places there are to put the energy as the temperature goes down.

Ben: So, the idea is that, how are we going to store the energy? So, Einstein comes along and Einstein goes, oh, the problem with this model, the reason it's not doing it correctly is because we're not quantizing how these particles are wiggling back and forth in place. Okay?

Anthony and Megan: Okay.

Ben: So, he's like, I'm going to apply quantum mechanics to each individual particle. So each particle kind of has a center location where it's supposed to live and it's going to vibrate back and forth. But instead of vibrating back and forth classically, it's going to vibrate back and forth quantum mechanically and that's going to affect how the system stores energy. You dig? So, he was wrong. Because he wasn't taking into account how if one particle moves a little bit to the right it's going to push on its neighbor, right?

Megan: Right.

Ben: And so you can have systems where all of them are moving to the right. Or you could have waves moving through the system. And so, Debye, what his insight is, so the question is, how do we model the system? Where is the energy being stored? Debye said, instead of individual atoms wiggling back and forth, we're going to treat this crystal like it's a box. And this box is holding a whole bunch of psuedoparticles, but particles, little bosons. Phonons actually, right? And so you say hey, what are the statistical, mechanical properties? How does box full of these little phonon particles hold energy?

Fiona: Wait, that just, sorry, I need to say one thing which is... So, in the Einstein model, you know, there were still bosons but they weren't, the excitations of each atom are still bosons in the Einstein model but these bosons were not interacting with each other. And then in the Debye model you know he treated them quantum mechanically, they were bosons, but they were also interacting. The model that Einstein quantized would be the equivalent of basically modeling your solid as a large egg carton and you but like a little bead in each egg cup, okay. And that bead can vibrate around in its own little egg cup but its vibrations are not in anyway correlated with the vibrations of the beads in the surrounding egg cups. So, even that model, when you introduce quantum mechanics, is not too bad. But Debye's model actually, basically, you know, more or less quantized this model of beads attached by springs.

Anthony: So he got rid of the egg cup walls.

Fiona: Yeah, he replaced the cups in the egg carton by springs. And the difference is if you have a bead in its own little kind of dip it just does its own thing. You put some energy in and it bounces around in its own egg cup. Whereas if you replace those cups with springs then if you put some energy in a bead moves relative to its neighbor. Right, and so for example, if you, if I take my egg carton model and I put some energy in at one particular, at one particular cup. So, I take a ball in one of the cups and I give it a push and it starts moving that energy is not going to go anywhere. Right, it's just that ball is moving, it doesn't talk to any of its neighbors so they're all just doing whatever they were before. Whereas when the balls, when the beads are connected by springs then if I push one bead, right, then it's like kind of if you tap on the surface of a trampoline or something you're going to see this energy propagate through the system.

Anthony: Okay.

Fiona: Does that make sense?

Anthony and Megan: Yeah.

Ben: So, the moral of the story is, when we quantize the sound waves, essentially, the waves through the system, the up and down waves, when one object pushes on another and you get waves moving through the system. Once you quantize those and treat the system as a whole as one that can store energy in those waves you can properly account for how the heat capacity depends on temperature. So, the moral of the story is you have to treat the assembly of waves that are moving through your crystal as particles, in themselves, pseudoparticles.

Fiona: As quantum mechanical particles right, not just...

[31:20]

Ben: So, as quantum mechanical particles and in doing so you end up with the proper relationship. So, the moral of the story is, yeah, mathematically you have to say hey, these vibrations aren't just us speaking rhetorically and saying hey it's like the way a wave is a particle or a tornado or a horse is a particle. It's us saying you have to treat these waves as individual particles inside the system or you don't get the proper theoretical result matching the experiment. So, in some mathematical but very real sense, phonons are particles.

Megan: Okay.

Anthony: Yeah. So, what is it you're doing when you say we're going to treat them as quantum mechanical particles. Like what quantum mechanical property is that you are ascribing to them that sort of changes it from no longer being classically tied together with balls and springs but instead they're acting as one. But what is it about the system that's quantum?

Fiona: So, basically, when we think about particles, we have this idea that, you know, like, maybe billiard balls on a table or something like that, right, where...

Anthony: Right.

Fiona: Even if all my billiard balls had the same number, right, there would still be a real sense in which, you know, I could say this particular billiard ball is here and that other billiard ball is over there...

Anthony: Right.

Fiona: And it turns out that quantum mechanical particles don't behave that way. So, basically, when particles are quantum mechanical there's really, there's no way that you can tell, if you have two particles and they're at positions A and B, there's no sense in which particle one is at position A and particle two is at position B. Because that's completely equivalent to having a particle two at position A and a particle one at position B.

Anthony: So are they both at A and B?

Fiona: Yeah. So, basically in a sense, you just think of both particles as simultaneously being at both locations. And, in other words, the particles are what we call indistinguishable. So, you know, there's just no, no sense in saying this is particle number one and particle number two and they're really different.

Anthony: And we're referring to the phonons here, like the particlelization of the wave of the movement, of the actual particles in the crystal lattice.

Fiona: That's right. So, yeah, in this case those are the particles that we have in mind although the statement about indistinguishability is a very general property of any particle at the quantum mechanical level. Um, but it turns out that the fact that they are indistinguishable has a big impact on basically the number of particles that are going to have a given energy at a given temperature. The fact that they are indistinguishable, which is a property of quantum mechanical particles, is what makes the heat capacity different at low temperatures from what the classical model predicts.

Anthony: Okay. I'm not sure I understand how decreasing the temperature of say, let's say it's like a crystal, and then you add energy to it and now we have a heat capacity, let's say it's really, really low because we have a temperature that's really low for the crystal. I'm not sure how, like the phonons are applying to this situation. Like, how is it that because of that property, because of their quantum mechanical property, I can put just a little bit of an amount of energy in there and get 1° difference whereas if there was a higher temperature for the crystal then I would need to put more energy in, like... I'm not sure I understand the connection between how the phonons being quantized means that that affect is a reality.

Darren: Okay, so, electrons are similar. Like, you can't say this electron over here is blue and that one is red. An electron is an electron. And the difference between electrons and things like phonons, ah, when you swap two electrons you get an overall minus sign in the equations. When you swap two phonons or any other boson like light you don't get a minus sign, you get a plus sign. And one consequence of this is that multiple bosons can occupy the same energy level, that's not true of electrons. Every electron in the system has to have a completely separate set of quantum numbers describing what it's doing.

Anthony: Is that like the Pauli exclusion principle?

Darren: Exactly.

Anthony: Okay.

Darren: So, that applies to electrons and anything with half integer spin but a phonon has no spin angular momentum, it's just a bunch of stuff moving around.

Anthony: Right.

Darren: So, phonons, light or other particles that don't have overall spin like a Helium-4, for instance, they behave this way. And so you you can get into cases where you've got a whole bunch of them in the lowest energy level and so you can excite from the lowest to the highest and you've got a whole pile of stuff there. Whereas, with electrons you've filled them up to some specific energy level and you're always dealing with what's happening around where you finished filling them up.

Anthony: Okay, so like, when you decrease the temperature of the crystal lattice then when you add energy to the system then there's just more...

Darren: The phonons keep falling down in energy into the lowest levels.

Anthony: Right. There's a ton of phonons down there and when when you excite them then it's easier for it to increase the temperature because it's easier to propagate through the system.

[36:25]

Darren: In the case of phonons they can also just go away. But, in the case of electrons they can't go to lower energy levels because there's something there already. In the case of phonons they can so you're working with the levels that are at lowest energy. And if there's types of phonons that only exist at higher energy you just don't have any of those anymore at low temperatures.

Anthony: Okay.

Darren: So, optical phonons, for instance, are generally higher energy. When you go to lower temperature you don't have any phonons of that type anymore. Your energy is stored in the low energy modes because everything can move down into the low energy states.

Ben: I want to imagine this like a big block of jello that's jiggling, okay. So, imagine you've got a cube of jello. Ah, the optical modes are the kind of transverse wave. So they're the ripples that move across it whereas the...

Darren: If you're putting your finger on the surface and and moving it left and right.

Ben: Yeah, whereas the...

Darren: Acoustic is you giving it a flick

Ben: ... acoustic are compression waves so it's getting bigger and smaller. It's squishing. Right? Um, and you're saying that the left and right wiggling modes are higher energy. And so there's some statistics to how the system evolves as we extract energy from it where the side to side wiggles go away first and then eventually the compression waves get smaller and smaller and smaller until they all go away.

Anthony: And so, if you like put energy into the crystal you don't have access to those particular types of jiggles, the optical jiggles until you get to a certain energy?

Darren: At higher temperature you can access higher energy modes.

Anthony: And then that crystal has the capacity to basically store the energy in that additional way so that heat capacity increases.

Darren: Right. But if its cold those aren't available.

Ben: I'm glad I introduced jello.

Darren: Well, there's always room for jello.

Ben: Let's move onto other applications and stuff.

Fiona: Well, I think we should say a little bit about superconductivity which is one of the most exciting kind of consequences if you will.

Darren: So, in a superconductor what's carrying electrical current is pairs of electrons. But the electrons, they don't like each other. They repel each other so something has to stick them together into a pair and in conventional superconductors that's a phonon. And the way that you can sort of see that this is connected with the lattice is the simple picture is if you have an electron moving through, it's negative. The nucleus of the atom is positive. They want to move toward it a little bit. So, you actually have this motion of the nuclei of the atoms toward the electron. The electron zips away somewhere and then some other electron sees this concentration of positive charge because the nuclei moved towards this place where the other electron was. So, the second electron is attracted to the fact that the first electron was there. That's the very simple cartoonish picture but it's a coupling between the electrons and the lattice that's doing this. And this seems to be how the conventional superconductors pair their electrons. It's not the case for the high temperature superconductors and a few types of low temperature ones and the jury's out on a couple of other classes.

Anthony: When you say high temperatures, how high is that going now?

Darren: High temperature superconductors are liquid nitrogen temperature roughly so the transitions are 40 Kelvin on up to about 140.

Anthony: Oh. Cool.

Darren: For a low temperature physicist it's really, really hot. It's at the point where you could call it room temperature superconductivity if you've got a very, very cold room.

Anthony: So, I was trying to visualize what you were saying, like why the two electrons were paired. I'm not sure, like where did the first electron go? Like, it left and then the other one was like, oh, there's a space there where it's positively charged so it goes towards it but where did the first one go? Why did it leave in the first place?

Fiona: I think that maybe that one thing that could me said here is that in general, you know, if you think about an atom, you think about, you know, the atom has some electrons and you know if you just have the atom in a vacuum the electrons are bound close to the nucleus of the atom. In a metal, however, in fact some of the electrons are kind of stuck being near the nuclei but the electrons that actually conduct electricity, basically they're not committed to being close to any particular nucleus. So, in general they are kind of moving around in the crystal at all times. So you have expectation for the electron is that it is going to be itinerant so basically it's here now and it causes this positive charge locally and then it leaves because it was on its way somewhere anyway. And then another electron fills that positive charge and maybe it deviates from its previous trajectory a little bit to visit this positively charged region.

[41:32]

Anthony: And those two are paired together because they are following each other bouncing in between these positive charges?

Fiona: Ah, yeah, essentially. Basically what has to happen is that the energy of this kind of standing in each other's periphery to benefit from each this charge cloud kind of has to be bigger than a kind of random. It's kind of an approximate picture but you know you can imagine these electrons having some, you know, random energy as they move around. But basically if you get cold enough then yeah, this is the glue that binds this pair of electrons together.

Ben: Megan and Anthony, do you remember your basics about superconductivity?

Megan: We just listened to it.

Anthony: Ah, just no resistivity when the electrons are going through the superconductor.

Ben: Uhhuh. Do you remember about cooper pairs?

Anthony: Uh, no.

Darren: Ah, so the particle that's actually transmitting the current is a combination of two electrons and at least part of a phonon.

Ben: So, to bring it back to what we were talking about before, you know how Darren was like, there these bosons and then there are these electrons. So, phonons are an example of bosons. And he was talking about the statistics of what happens, of how an electron will behave differently than a phonon will when you cool it down.

Anthony: Right, because it can't, like, go to a lower state of energy because there's something already there.

Ben: That's right.

Anthony: And since they occupy the same quantum state it can't be in that space, so it has to stay in the upper energy level.

Ben: Perfect, yeah, exactly. So, the difference between those two types of different particles, one of them are called fermions and the other bosons. Electrons are fermions and phonons are an example of a boson, is that one of them has one half integer spin so the spin of an electron is 1/2 and that means it has to obey the Pauli exclusion principle and a phonon has spin zero, or, things that have spin 0 or spin 1, those are bosons and they don't. And they can all go to the lowest energy level. So, what happens inside a superconductor is that all of the electrons.

Darren: Two halves make a whole.

Ben: Yeah, all of the electrons in it combine. So, they kind of get partnered up and when they partner up then, combined, they have an integer spin and they start acting like bosons. And so, even though on their own each electron will stack up in that way you were describing because of Pauli, once they combine up you can bring those pairs all down to the lowest energy level.

Anthony: Yeah, that makes sense.

Ben: And then when they do, they all act exactly the same way and you get this large scale superconductivity property. And, so what Darren is saying is, the question here is how the two electrons pair up. When they pair up it's called a Cooper Pair. And what he's saying is they pair up because a phonon sticks them together.

Megan: Oh, okay.

Anthony: So we were describing like what a phonon is earlier and it was sort of like this representation, it was like a wave, like going through a physical system. Like, what is it in this context, like what is a phonon between the two electrons?

Fiona: Ah, the phonon is basically describing a wave in which, so if you think about, you know, the wave in the slinky?

Anthony: Yeah.

Megan: Right.

Fiona: You know, you can think of, for example, a compression and so that's going to bring, if you put beads at fixed distances apart on the slinky then as the wave comes through some of those beads are actually going to be closer together. And then, you know, some of them are going to be farther apart. So the phonon is describing that process in which the distance between two adjacent atoms gets you know, either compressed or expanded. So, basically, the reason that this couples two electrons is that, you know, an electron has a negative charge. So, if you have an electron that's sort of hanging out, for example, between two atoms on a lattice then that's actually going to pull those two atoms in towards it. So, basically that pulling motion, if you like, is kind of exciting a phonon.

Anthony: Okay.

Darren: The phonon exists over the entire material and so do the electrons. So, we can sort of justify it very locally at one site but overall the electrons and the phonon, they're waves, they're covering the whole material.

Anthony: Okay.

Darren: So they're doing this over some spacing. You can imagine this happening at one location in space but it's also happening in a bunch of others at the same time.

Anthony: Because it's, I mean, it's all the same thing at that point. I mean, it's a quantum system.

Darren: The electrons are spread out over everything.

Anthony: Right.

Darren: As are the phonons.

Anthony: Well, with superconductors, like the way that I understood it from when we listened to the other episode, the electrons were moving. So, I mean, they're everywhere but they're also moving, right?

Darren: Yeah.

Anthony: Like they're... right.

Darren: They're a wave and the have momentum in that wave.

Ben: Darren, do we want to go through all these other examples of uses.

Darren: We mentioned that the acoustic phonons kind of look like sound waves. They do actually carry sound. So, if you're moving sound through a solid it's traveling in phonons.

Anthony: Ah, that's cool.

Darren: And we mentioned heat capacity, you're storing heat in these materials, in the phonons and so heat is traveling through the material as phonons. And, it turns out, one of the big limiting factors in making computer chips, particularly processors, is the ability to get heat out.

[46:38]

Megan: Right.

Darren: So, if you really want to get heat out as effectively as possible, phonons are actually something you need to think about. Because that's how you're doing it.

Megan: Huh.

Darren: So, I think that tends to be the higher energy phonons. The lower energy ones are probably kind of saturated by room temperature. But they need to think about parts of the phonon spectrum for the material they're working with and how they can best get heat out of the material.

Anthony: Huh.

Megan: That's cool.

Darren: I guess one other thing that we could mention is there's some types of structural phase transition where the, if we had balls on springs where everything is in a nice cubic grid, there are some types of materials where at low temperature it turns into something else where you know, maybe the balls want to pair up in a specific way or something and the way a few types of this transition work is, so you've got some central ball and it's got it's arms out and it's got a phonon where one arm is out to the left while the other one is in to the right. And then it switches so that the right arm is out and the left arm is in and it's just sort of going back and forth, punching the air in both directions.

Anthony: Right.

Darren: You know, maybe this phonon mode actually freezes out at some temperature and this thing is stuck with its right arm out. And so this has happened throughout the crystal and you've basically gone through a structural transition and now everything is in a pair because it's holding the thing on it's left much closer.

Fiona: So, actually effectively what, it changes the structure of the crystal because it changes the location where the atoms kind of spend most of their time.

Anthony: So, if they get stuck there and then, does it only change the structure of the crystal at that temperature and then when you increase the temperature, by increasing the energy, the structure changes back to how it was?

Fiona: Yep, yep, it can melt. Yep.

Ben: Well, that was fantastic. Okay, so, thank you Fiona, thank you Darren. You've pleased me. Your efforts have borne fruit and that fruit is sweet, here is some fruit. Fiona, you get a coconut!

Fiona: (Sound of some sort.)

Ben: Good. And Darren, you get a kiwi.

Darren: (Munching sound.)

Laughter.

Ben: Alright, I'd like to thank my guests, Anthony and Megan Leon, thank you very much Anthony and Megan for coming on the show!

Anthony: Thank you, it was fun.

Megan: Thank you. This was awesome.

Ben: Alright! Hey everyone. Well, that was the first episode of Season 6. I've lined up a whole year's worth of fantastic episodes for us to record and I can't wait. Alright, so, it's announcement time. First, please give as an iTunes review and tell other people about us online. Why? Because people keep their deep love of physics secret. They want to know that there's a show like ours online but they don't know that we exist. A subset of your friends and family will be really happy to hear about us and the rest of them, well, I'm sure they'll endure you talking about a physics podcast you like because they love you.

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Ah, you can send one-time donations through PayPal off our website or you can go to our sweet Patreon site and give a recurring $2 donation or whatever. Speaking of which, this particular episode of the Titanium Physicists has been sponsored by a collection of very generous people. I'd like to thank the generosity of Weena Brett, Elizabeth Hargrave, and Jordon Young for their donations. And I'd also like to thank Keegan Yad, Adrian Shonig, Adrian Bastias, Cadby, Joe Campbell, Alexandra Zany, Weena Brett, Eric Duch, Atein Raymond and a gentleman named Peter. Mr. Gareth Easton, Joe Piston, David Johnson and Anthony Leon as well as Doug Bee, Julia Nora Robertson, Ian and Stu. A Mr. Frank, Phillip from Austria and Noisy Mime. Mr. Shlowmo Delow, Melissa Burke, Yaseem Omarasazee, Spider Rogue, Sandy Orbitz, Robin Johnson, Sandra Johnson, Mr. Jacob Wick, a Mr. Jon Keyes, a Mr. Victor C, Ryan Klaus, Peter Clipsham, Mr. Robert Haupen, Elizabeth Theresa, and Paul Carr. A Mr. Ryan Knewl, a Mr. Adam Cate, Thomas Shiray, a Mr. Jacob S, a gentleman named Brett Evans, a lady named Jil, a gentleman named Greg, thanks Steve, a Mr. James Clausen, a Mr. Devon North, a gentleman named Scot, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Rob Arizato, a Mr. Robert Stietka. So, that's it for Ti-Phy this time.

Remember that if you like listening to scientists talking about science in their own words there are lots of other lovely shows on the Brachiolope Media Network. The intro song to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Good day my friends and until next time remember to keep science in your hearts.

[52:53]

Anthony: So Megan was saying, we were, she was reading about phonons a few days ago and she said that somebody was making like some sort of singularity or black hole out of phonons?

Megan: Oh yeah, that's right.

Anthony: I was wondering if you guys had ever read anything about that.

Fiona: Oh, Ben should answer that because that's, that's Bill Unruh's thing, right?

Megan: Yeah... he designed it I think?

Ben: Okay, hold on

Megan: I can't remember who actually did it.

Fiona: I think he calls it the dumb hole. I might be thinking of the wrong thing. I actually saw him give this talk once where he was explaining blackholes and he had this picture, I actually really love this picture. The picture involves, so you have a river and um water is moving at some speed and there are fish in the river okay.

Anthony and Megan: Right.

Fiona: And there's like, basically there's a water fall okay. But, okay, so the fish are in the river and they're trying to swim upstream but the current is moving faster than they are swimming. And then you imagine a scenario where you know the fish, so they're getting frustrated obviously, they're not getting up the river, and so they start to scream. Okay, so, they're screaming and that's creating this sound wave that's, you know, propagating forward from the mouth of the fish. And so the question is, what is a black hole? Well, a black hole is like the scenario where the water is moving so fast that you know the fish screams and you have this sound wave coming out of the fish's mouth but the current is so fast that the sound wave is also propagating downstream so like a fish or you know, if you put a microphone upstream, once your fish has gone past that microphone and its screams you're never going to hear the fish scream because every time... moving down stream so fast.

Anthony: If the fish is screaming upstream and the microphone is down steam you'll hear it but once you get past the microphone then you won't hear it because the stream is carrying the wave faster than it can propagate through the water.

Fiona: Yeah. And that's a little bit like the situation in a black hole where if you fall inside the black hole and you try to shine a light out, um, you know, you have a friend who's outside the black hole and you want to signal SOS with your flashlight, but that light is never going to make it to your friend because your friend is on the other side of the horizon and the light will never get out of the horizon.

Ben: Yes.

Anthony: And so we've got something similar with phonons.

Ben: Okay, yeah...

Fiona: People actually made it?

Ben: Yeah. Yeah, yeah, yeah. Okay, so...

Anthony: Okay, cool.

Ben: What you're talking about... you called it a dumb hole, right?

Fiona: I thought I was, it was Bill Unruh's thing, I'm pretty sure.

Ben: Yeah, that's the name of the model. So, Bill Unruh, he had started out as an analogy that he would use to explain blackholes to lay people. Which is just this kind of fish thing so it's like once the fish is over the horizon, once it's far enough down the water fall it can't talk to anybody because the water is moving faster down than the sound waves can move up. Right? Which is what you just said Fiona. So, it turns out that it's a little bit more than that. The analogy is actually really incisive. You can build mathematical analogs for how blackholes work using sound waves. So, you don't necessarily need to make a waterfall. Because the rate that sound passes through the water depends on things like the flow rate and the temperature and how tall it is and all sorts of things. But you can build, in a laboratory, other systems that are mathematically analogous to black holes. So you can build these sonic blackholes where water is flowing through the system in a way that waves travel through the system in the same way analogously that they might evolve in and around a black hole. And what this lets you do is, it lets you test all sorts of predictions that people have made about black holes. Stephen Hawking made a prediction that black holes emit a certain radiation. And so what this has let people do is it lets them test to see if in this mathematical analog, in this sonic black hole, the mathematical equivalent to that Hawking radiation actually gets generated and they've detected it. And it's actually a really interesting thing.

Megan: That's really cool.

Ben: Anyway, the moral of the story is...

Darren: They detected acoustic Hawking radiation.

Ben: Yeah, that's right.

Laughter.

Ben: Acoustic Hawking radiation.

Megan: That's awesome.

Ben: Which is awesome, yeah.

Anthony: A lot simpler than touching a real black hole.

Ben: Yeah.