Episode 23: Quantum Tunneling
Physicists: Henry Reich, Tia Miceli
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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 that 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]
In the world of classical one very common, very useful concept is that of the potential barrier. Okay, so what's that? It's a strange phrase: potential barrier. Potential is short for potential energy. Barrier is short for barrier. It's a way to describe a feature that some systems have, systems where your object can't move past a certain point if they don't have enough energy. So, hills. Hills for kids on bikes are often potential barriers. When I was a kid I had a bike with only one gear so if you were climbing a hill, you couldn't change gears. So, if you wanted to get over a hill you had to get a running start and if you weren't moving fast enough at the bottom of the hill you'd slow down and come to a stop before you reached the top. So the hill was a potential barrier because if you had enough energy at the start you could make it over and cross the hill. But, if you didn't, you couldn't. So, in the world of physics potential barriers are everywhere. You know how if you throw a rock up in the air it will always fall back on your head unless you throw it faster than the escape velocity of the planet you're standing on? That's a potential barrier. So, what keeps to atoms combining and having one big nucleus? It's the electric fields emitted by the positively charged protons. They push against each other and that's a potential barrier. And what keeps two protons in the same nucleus from splitting up and pushing themselves apart and making two atoms from one? Well, there's a strong force sticking those protons together and that's a potential barrier. What keeps the water in your dog's dish from running out on the floor? Potential barrier. They're everywhere. Okay. So, until the 20th century came around the potential barrier was the law. The water inside the dog's bowl was stuck inside the dog's bowl and unless the dog came along and messily drank the water and gave some water some kinetic energy to slosh over the side the water would be stuck in the bowl forever. That's until quantum mechanics came along. Turns out, in some circumstances quantum mechanics tells us that a particle can walk right through a potential barrier even if it doesn't have enough energy to get through. This process is called quantum tunneling and that's the topic of today's show. So, today's guest is an artist who's work I have enjoyed for the better part of a decade. His current comic, the Non-Adventures of Wonderella details the annoying life of a sarcastic super heroine. The writing and art are both concise, efficient and hilarious and you can read it and buy the books at nonadventures.com. So, welcome to my show, Justin Pierce!

Justin: Hi everybody!

Ben: So, Justin, for you today I have assembled two very special Titanium Physicists and we've got a real treat. Arise Henry Reich! Fantastic! In the world of internet physics outreach there's only one king. With half a million subscribers on youtube and 35 million views, he is the creator of the popular Minute Physics videos. Henry got his Masters in multi-metric gravity from the Perimeter Institute of Theoretical Physics and he's currently employed there as the artist in residence making little videos to entertain and educate you. Now, arise Tia Miceli! Awesome! Tia is a graduate student at the University of California Davis where she studies high energy experimental particle physics and she's writing her thesis and zed decays. Okay, done the intro. Alright Henry, we've got to introduce wave functions. How are we gonna do it?

Henry: Well, my favorite way of talking about quantum mechanics in general is to talk, not in the standard way that most physicists are used to thinking about it, but using a picture called Bohmian mechanics which is equivalent to regular quantum mechanics mathematically, it just gives you a different intuition as to what's going on. Traditionally we are used to thinking about particles as things that move around and bump and have a very definite trajectory. They go one way and then they go another way. We always was know where they are and how fast they're going. And then waves, you know you have waves on a string, you have waves in the water and the waves are fluid and nebulous and they can interfere and do other wavelike things. And it turns out that in quantum mechanics particles don't always behave like particles. They kind of are guided buy these things which we call wave functions but basically the picture that like to have you think about is, imagine a rain drop and the raindrop has a speck of dust in it. So the speck of dust is our particle and the raindrop is the wave function. And when you start off you know where the particle is, it is somewhere in that raindrop and it's fairly well contained. But say the rain drop falls on the ground that water will get spread out and splash around. You could know exactly where all of the water is but that doesn't tell you with a speck of dust is. You just know that if there is more water in one place that's where you're more likely to find the speck of dust if you look for it. That's roughly how quantum mechanics works. The wave function is guided by, in general, complex equations depending on the situation. But all you have to know is, figure out what the wave function, which is our distribution of water, figure out what that looks like and find the speck of dust in it and that's where the particle is.

[7:01]

Justin: So is wave function just entirely random then or is there a rational explanation for why there would be some segment of the raindrop that has this particle in it?

Henry: So that is an incredibly good question as to the underlying nature of quantum mechanics. At the moment the best we know is that the particle just randomly is somewhere when you look for and if you do the same thing twice it could be in different parts of the water at different times. It's kind of like running the experiment multiple times the fleck of dust might end up somewhere else.

Tia: So the wave function is the water drop, right?

Henry: Yes, the wave function is the water drop in this picture and the particle is basically, it's guided by the way this is the picture and this is this is very counter to what, to pretty much what anyone who takes undergraduate physics is taught. It's a very different picture but it's mathematically equivalent and I find that it's much more intuitive and easier to picture.You just have to say, well we have this amount of water and the particle is somewhere in this drop, and the drop gets spread out according to the Schrodinger equation and once you know where the drop has gone, if you want to know where the particle is, if there is a lot of water somewhere that is where you are most likely to find it. If there is not a lot of water you're less likely to find the particle there.

Tia: I like it. I like it.

Ben: That's A great introduction. OK so sometimes in physics you end up with situations where there are some forces holding you in but if you can make it out past a certain distance you can escape. These are the potential barriers I mentioned before. So for example there is a great one which involves nuclear forces for protons. So if you imagine an atom, it's got a nucleus and the nucleus is made up, essentially, of a whole bunch of different protons that are stuck together. And protons have a positive charge and the thing about electric charge is the closer two positive charges get together, so if you rub your head against two balloons and you try to push them together, the closer together they get the more of a force they feel pushing them apart. Okay, so, as these two nucleons, they're both positive, the closer they get together the more of a force they feel pushing them apart. But when you get them close enough together, a nuclear force kicks in, called the strong nuclear force, it kind of sticks these positive protons together.

Tia: So one analogy I've heard for this is if you have charged ping-pong balls. Of course if they have the same charge they repel but if these ping-pong balls are coated with Velcro then if they get close enough the Velcro sticks just like the strong nuclear force.

Ben: Right.

Justin: So there is the threshold where it's like if they are sort of close together they'll repel but once then once they are actually almost touching they will attract each other once they get past some barrier.

Tia: Yeah.

Ben: Right. And so this threshold is the barrier. This is the potential barrier in the system and it's spherical so all you need to do, in any direction, if you take these two protons that are stuck together and move them just far enough away from each other that the electric force between the two kicks in, once you're past that threshold, they will just move away from each other. So in this situation, essentially, these particles they might have a little kinetic energy and what that kinetic energy will make them do is it will make them kind of vibrate around each other. If they're stuck together it means that they don't have enough kinetic energy to get far enough apart so that they can separate so they just kind of jiggle around together. Classically speaking this is kind of what's happening and what it means in the classical picture is that they will be stuck together forever.

Justin: So, the idea is that, like these two balloons that are sort of like, almost touching and they're just sort of hovering very close to each other. The barrier that they need to get over is something to keep them far enough apart so that they'll repel again.

Tia: Yeah.

Ben: The barrier is essentially the need to get past a certain distance.

Justin: Okay

Ben: It's equivalent to say having to ride overhill with your bicycle. If you don't have enough speed you can't make it up and over the hill. So I've got a glass of water in front of me and so I imagine this side of this glass of water as being the potential barrier. If the water can make it just outside this class cylinder it could go where ever it wanted to. So in the case of the nucleus it's just like that. You have these different protons and they're stuck inside the nucleus jiggling back-and-forth they want to get out but their quantum mechanical objects and so in this Bohmian mechanics picture we envisioned it, in this case, imagine a cup that has some water in it and that represents the wave function. You don't know where, inside this cylinder, you're going to find the nucleons but you know based on how the water is distributed where the particle has a better chance of being and where it has a worse chance of being.

Justin: Like if it's a wineglass there is going to be the wider part and there's going to be the skinnier part it's probably going to be in the wider part just because there's more area.

Ben: Yeah. Now we got to talk about tunneling through this thing. So we have introduced this idea of a wave function where the wave function kind of carries around the particle. So if you have the wine glass the chance is that the particle is going to be where with the column of wine is higher is larger than when the column of wine is smaller.

[12:18]

Justin: Right.

Ben: So the deal with quantum mechanics is there, are few rules that govern how the wine, this liquid can evolve. There is one simple rule in this case that always governs how this water will distribute itself or how this wine will distribute itself. Which is that this volume of water can't have a sudden transition where there is water in one place, and then no water right next to it. In other words, so, it can't go to zero all of a sudden. In this quantum water what you imagine is there is water in the middle of the glass then there is that glass wall, the edge of the glass but because of this rule that says that the water can't have a sudden transition to zero it means that there has to be a little bit of water just inside the glass wall and that just inside that there can be a little less water.

Justin: So, there's like these, like this glass in this example would be like have like tiny pits in the edges that were microscopic, and little nooks and crannies for the water to hide as you get out to the glass edge or something. Is it like a slow gradient?

Ben: Yeah, that's right.

Tia: Yeah, and as you go deeper into the glass the little holes where the water is allowed to be get smaller and smaller so you have a smaller probability of finding that dust particle within the glass.

Justin: Okay, at the very very edges of the glass.

Ben: Yeah.

Henry: I just break-in, make a point as nice as this explanation is, the holes actually come from the water and the glass doesn't have the holes in it originally in the quantum mechanical picture.

I'm wondering whether something, we talk about it like a sponge. And a sponge has an even amount of holes all the way through it but if water only travels from one point of the sponge to the next, in kind of lower and lower concentrations. You know if there's a little bit of water in one part of the sponge, there will be, a little bit of it will seep out to the next side of the sponge and a little bit of that seep farther and so you have less and less water the farther through this sponge you go.

Ben: Right. So the side of the sponge that is touching the liquid will be really wet and then that part of the sponge that isn't directly touching liquid will get less and less damp the farther away from the liquid you go.

Justin: So, what you guys are saying is that it's the water is the thing that's pushing out it's not a particular pitting on the container or on the wall its action by the waveform what happens to be like water or something that's forcing this gradient to be happening.

Ben: Yeah. That's right.

Henry: Exactly.

Ben: It's fundamental to this wave function that it won't let you transition to no probability. So if it's possible that the particle could be right at the edge of the glass wall then it's also going to be a little bit possible that the particle could be inside the glass wall. The deeper you go into the glass the probability that the water will be there decreases the farther you go. So, in essence what happens is let's say you have a glass wall that has only a finite width like a mug that you're drinking water out of. What this means is that the water will permeate the mug wall and it will also kind of flow outside the mug, it will use these kind of holes that it makes and as a result there's a chance that there's a little bit of water we'll be outside the mug. So, because there is water inside the mug there will also be a little bit of water inside the walls of the mug and then there will be even less water but it will be possible that there could be water outside the mug.

Justin: Sure.

Ben: This means that if there is water outside of the mug in the description of quantum mechanics that we have been giving you, the particle itself, that dust particle that's living inside the water, so if there is water outside of the mug it means that there is a finite probability that the particle could be outside of the mug.

Justin: Okay, that is the part of the water that sort of worms its way through the surface of its container that within that it could contain this particle of dust.

Ben: Yeah.

Tia: Yeah.

Ben: Because of the water's nature this particle of dust can end up outside the mug even though it didn't have enough energy to get over the wall.

Justin: One of the main parts of this is the fact that this particle, on its own, would not be able to surmount whatever the wall the difficulty is this guiding it through.

Ben: That’s right, it wouldn't be able to make it past the threshold if it wasn't for the nature of the water that carries it around.

Henry: If were a classical, non-quantum mechanical particle it would be stuck there, it would never be able to escape. But it has this slight chance, because it's a quantum mechanical particle, it has a slight chance of being able to be outside of the glass.

Justin: There’s never going to be an outside force, like say that dog that sticks its head in the water and pushes it over or somebody that like bats one of the balloons away from the other with their hand, is it always going to be, just basically be sort of unlikely but possible way for the wave to push something through on its own or is there going to be some outside force pushes it.

Henry: If there were an outside force that wouldn't be quantum tunneling that would be regular quantum mechanics.

Justin: An outside catalyst like someone he knocks the mug over accidentally or something that wouldn't be an example of this right? It would have to be the water on its own seeping through the barrier.

[17:23]

Ben: Yeah.

Henry: Exactly.

Justin: Okay. I think it makes sense. I don't really know how it fits into much, because it seems like such a small probability of it happening.

Henry: Yeah, one of the big ideas is that it's such a tiny probability that it only happens very rarely so a lot of where this affects, plays an important role are places where there are tons of particles and only a couple of them actually manage to tunnel through and do the interesting things.

Justin: Okay, that makes sense I was trying to figure out the scope of this because it seems like hitting a racquetball at a wall a thousand times and then you know after 100,000 times somehow it makes it through the wall or something, like it just seems like almost an infinite chance that it we would never happen you know.

Ben: Tia, it's time to talk about your beer.

Tia: Okay. So before the show I calculated how long it would take a cold can of beer to tip over by quantum tunneling. And it would take 10^{31} years. To put that in perspective, the universe is 10^9 years old, a billion years. So, it would take your can of beer sitting there, what was it, hundred million trillion trillion years to tip over.

Justin: One with 31 zeros after it years.

Tia: Yeah. So when physicists like to say that while anything is possible, my cat can tunnel through the wall, well sure your cat can tunnel through the wall but it might take many, many many life times of the universes for that to happen.

Justin: So when a scientist tells you that something is possible that doesn't necessarily mean that it's ever going to happen anytime in your lifetime or is anyone you knows lifetime.

Ben: So let's get into fun examples of quantum tunneling. So there was a mystery about the sun which was so how does the sun burn. Do you know the answer Justin?

Justin: Yeah, the sun is some mishmash of crap in the core.

Ben: Yeah, nuclear fusion. They're hydrogen atoms that are mushing together and forming helium atoms. Figuring that out itself was a mystery. When they figured that out though, they said, okay I've described before this kind of potential well to get two protons together right. So, there is this electric force between them and it gets stronger and stronger the closer you push them together but if you can get them close enough together the nuclear force will stick them together. So, I calculated how much temperature that would require. So, temperature is kind of a gauge of how much energy each particle in a gas on average has. They could say okay if takes so much energy for two protons smashing together to fuse how much temperature would it require and the answer is 400,000,000° Kelvin because of this potential barrier, 400,000,000° Kelvin. The thing is the sun in the core is only 15,000,000° Kelvin. So you need 400 but you only have 15 million degrees Kelvin.

Justin: Is that like a weird anomaly or does it go to any sort of fluctuations like this on a normal basis?

Henry: It doesn't suddenly get 100 times hotter and then cool off again.

Ben: Yeah, it's business as usual on the sun. And so they have this hundred times colder than you would need for nuclear fusion. So what's happening is tunneling. You know it's a rare effect but on the inside of the Sun there're lots and lots and lots of hydrogen atoms smashing together. It's really dense and it's happening a lot because the sun is huge. So even though it's rare and even though these two protons are too cool, they're not energetic enough to smash together and melt and form helium nucleus, they get close enough that they can tunnel into one another. So, effectively even though it's a rare enough event the sun has enough particles on the inside of it that this is a regular occurrence and that's why the sun is burning.

Justin: Oh really, so that is really the explanation for why the sun exists as it is.

Henry: Quantum tunneling.

Ben: Quantum tunneling let's it happen.

Henry: And so, one interesting side effect of this is this is partly why it's so hard for us to make fusion happened on the earth today controlled way like to generate electricity for example because we don't have enough stuff here on earth to be able to make it as dense as the sun. We can't take advantage of quantum tunneling so we need to get a fusion reaction to be 100 times hotter then the sun in order for it to do fusion properly. So this is why fusion it's hard because we have to get it much hotter than the sun because we don't have as much stuff as the sun does we can't rely on quantum tunneling to help us with our fusion on earth.

Justin: Is this reaction what kickstarts the sun originally or is this what keeps the sun constantly going?

Henry: This is the way the sun works everyday, day in and day out. The sun is mainly hydrogen and a little bit of helium so that's how it is able to burn. The sun were made up something like gasoline or wood and it was just burning even as huge as the sun is it would burn out in a 1000 years. So, the way it can stay going so long is because it's actually only very few hydrogen atoms that are fusing together.

[22:42]

Justin: Okay. So it's one of those things where it's, even as rare occurrence as this quantum tunneling is, on something like the core of the sun there's just so much stuff to work with there that it's happening in an ongoing basis.

Henry: I mean it's like if you have a one in 1 million chance but you try it 10 trillion times you're going to have it happen a lot.

Justin: Sure. It's gonna happen.

Ben: So, Justin. There is a mystery for people when they were talking about nuclear decay. So, in essence you start off with a heavy nucleus like uranium. Imagine a collection of uranium atoms as like popcorn kernels at the bottom of a bowl. So you have a big bowl of un-popped popcorn kernels and then at random they pop. So, the deal is when you pop popcorn on the stove the rate at which they pop depends on how hot it is but with uranium atoms and other radioactive atoms nothing seems to matter, there's kind of a universal time scale at which things pop. You've heard of half-life right?

Justin: Yeah, it's the amount of time it takes for something to decay right?

Ben: Yeah.

Justin: 50% or something.

Ben: Right. So all it says is if you take one of these uranium kernels the half-life is four years or whatever, you wait four years, there's a 50% chance that popcorn kernel is going to pop and turn into two different smaller atoms. In the five years after that there is, of the 50% of popcorn kernels that didn't pop in the first five years, half of them will pop in the next.

Justin: So, like the grannies will eventually pop as time goes on.

Ben: Yeah, as time goes on. But the deal is that, essentially, it's a pure statistics game whether or not it's going to pop or not. So there's kind of a mystery as to why it was such a pure mechanism, why there was such a pure probability regardless of how hot it was outside, regardless of how much oil you poured on the uranium atom, 50% of them will always pop within this amount of time.

Henry: I think the crux of it is that there are a whole bunch of protons and neutrons that are bound together in the nucleus of the uranium right. You can imagine if you could somehow split off some of those protons, the protons will get far enough away that the nuclear force would be really, really weak and the electromagnetic force of repulsion from all those other protons in the nucleus would be big enough to shoot that proton far away. So this is the barrier that we are talking about. There is a chance that you would quantum tunnel through this barrier and there is a time scale that governs how likely it is that in this X amount of years you'll have a 50% chance of tunneling out. So for each nucleus at any point in time in say the next five years there's a 50% chance that in the next five years it will decay and a 50% chance that it won't decay. And if it does decay then it's done and if it doesn't decay then in the next five years after that then there's another 50% chance, right, because it's continuously, it's the same thing, you start from scratch every instant that it hasn't decayed you start from scratch. But because you have so many of them, you know, because there was a 50% chance of it decaying in five years in five years than half of them will I have decayed and half of them won't.

Justin: Right, it's like flipping a coin there's a 50% chance you flip it and the ones that don't get the heads that you want you flip it again and you're starting from square one.

Henry: Right you're flipping until all the coins get heads.

Justin: Right.

Tia: So, things decay. For example, uranium can decay into two smaller atoms, a thorium atom and a helium atom and we are able to predict how often this happens. But in order for this reaction to happen that helium atom that gets ejected from this big nucleus needs a certain amount of energy but physicists were surprised when they measured the energy of this helium atom because they found that it was six times smaller than what it needed to get ejected. So the question became how does a helium atom with such a small energy get ejected from this huge potential barrier. They use this idea of quantum tunneling to correctly predict how long it takes uranium 238 to decay into thorium and a helium nucleus. So this helium nucleus is just two protons and two neutrons, it's called an alpha particle. So you can model the potential of the uranium nucleus like this dog bowl, the nucleus is the center of the bowl and then the sloping edges is the repulsive electric force which would push this helium nucleus away if it could make it out there. So you can think of the uranium nucleus as having the same potential as the middle of the dog bowl and your alpha particle's kind of rattling around in there and it can't make it out but with quantum tunneling it doesn't have to go over the edge of the bowl, it can go through the bowl. And it doesn't penetrate very much but with how much it does penetrate it gives us the correct likelihood that the helium nucleus will make it out of the dog bowl and slide down the side and become a free nucleus all by itself separate from the original parent uranium nucleus. So that was kind of amazing

[28:12]

Ben: alright so there is one final example of quantum tunneling that's really sexy. It's called the scanning tunneling microscope. Have you seen those pictures of atoms lying flat on like a table? So I don't know if you know but people, people can take photographs… well they're not photographs but people can see atoms.

Henry: They can generate images.

Ben: They can generate images of individual atoms. Were you aware of this?

Justin: I guess. I like, I mean I assume that if I Google image search atoms there probably going to see pictures of atoms but I guess I wouldn't have known if they were actual atoms that somebody has captured, in like you know.

Ben: Okay.

Justin: In the real world versus just like an artist conceptual drawing or something.

Ben: Yeah. So the deal with atoms is they're too small to see with normal light. If you wanted to see them with light you would need a very small wavelength of light and usually small wavelengths of light and have a lot of energy. So if you try to look at an atom it would just, you would hit it with a photon in the atom would go flying. So, in essence microscopy is fairly limited in terms of our ability to see individual atoms. But there is this tool that people can use to see atoms and it's called a scanning tunneling microscope.

Tia: Okay so the scanning tunneling microscope works by, you probe a surface that has the atoms on it that you want to see. You probe it with a very, very, very fine wire that is whittled down to a very, very, very fine point that hopefully has just one atom on the end. And then you apply a voltage difference between the surface that you want to image in this very pointy tip and then you have a machine that brings this tip very close to the surface and when you get close enough to the surface you can have a tunneling affect between the electrons and the tip of your probe and the surface that you are probing. So when an electron makes that jump you get current flowing. Current is just the flow of electrons. So you record this current and that current will be proportional to the depth of the thing that you are probing, topography of the surface that you are imaging.

Justin: Because there is going to be more electrons through the thicker parts than the thinner parts.

Tia: Yeah, so if your surface is raised and you bring your probe close to it, you will have a higher chance of tunneling there then the places where the atoms are lower, deeper in the surface so they won't tunnel as far.

Ben: Have you ever been to, like you go to Toys "R" Us, and there is a big vertical bin that's full of kids balls and they're all like sticking out, usually there's like nylon rubber ropes or something hanging down did you know all the balls are kind of sticking out. So that's what the surface of anything made out of atoms looks like, at close enough distance. Now, this isn't a distance we can see optically.

Justin: Right.

Ben: But, the deal is if you, essentially the scanning tunneling microscope, it's kind of like dragging a record needle near the surface. So as you drag this needle over the surface of this box full of balls when it's close to the edge of a ball it will tunnel better and when it's faraway from a ball it will tunnel worse. And so you can use that to figure out where the edges are higher and where they are…

Justin: Like depth finder or something.

Ben: Yeah, that's right.

Tia: Yeah

Ben: And in essence they drag the needle, like microns above the surface, and then they go back and they move the thing up a little bit and scan back across it and they just kind of paint the surface back and forth with this needle and then they do some computations and they can use that to figure out how far the needle has been from the top of the surface. From that you can end up with pictures of atoms.

Tia: Yeah.

Justin: That’s cool, so it works the same way the scanner would it just sort of passes through in several sweeps and then sort of comes up with the map based on those sweeps.

Henry: Exactly.

Tia: Yeah. Exactly.

Justin: Okay. When we get pictures of atoms that's basically the process they're using. They're sweeping over the surface and making sort of a bass relief of terrain on it, to show the nooks and crannies I guess.

Tia: Yeah.

Henry: Exactly.

Justin: Okay.

Ben: Okay, any other questions?

[33:11]

Justin: The weird thing about this is such a rare occurrence but when you're talking about the scale of the things that you are working with, whether it's the sun or you know there’s such an almost infinite number of chances for it to happen that it just becomes a regular occurrence, that's the most bizarre part about this you know.

Henry: Well it's like somebody has to win the lottery. It's a very small chance for you to win the lottery but normally somebody does.

Justin: Exactly.

Ben: It depends on the circumstances. When you're like a kid riding over hills, some hills are easier to ride over then others. And the ones that are easier to ride over are the ones that we'll be tunneled through faster, that will be tunneled through more easily. So, mashing two hydrogen atoms together to make a helium atom, that's a lot of tunneling so that will be a really, really rare occurrence. So, the sun can do it because there's so much hydrogen inside the sun. On the other hand if you take a really, really radioactive, like one of these isotopes that lasts, that has a half life of like five minutes, so they're decaying through tunneling process but the chances of that tunneling affect happening are really high and so they'll all total really fast like playing the lottery with the odds of you winning are 1 in 6 versus one in 6 million.

Justin: Yeah.

Ben: So, it's not always a really rare event. It really depends on the circumstances, it really depends on this potential barrier that you need to get through.

Justin: Okay.

Ben: Well that was great. So thank you Henry, thank you Tia. You have pleased me. Your efforts have born fruit and that fruit is sweet. Here is some fruit some spiky fruit that's hard to get into. Henry you get a durian.

Henry: Owww!

Ben: Yeah I use a machete or something. Tia you get a rambutan.

Tia: Ooooouuuuch. Ouch. Ouch. Ouch. Ouch.

Ben: They're not that spiky, they are just kind of spiky. Anyway, enjoy your rambutan.

Laughter

Ben: I'd like to thank my guest Justin Pierce, thanks Justin.

Justin: Thanks for having me on.

Ben: I hope you had fun. We have lots of fun.

Laughter.

Ben: Okay. Alright, everybody, my Ti-Phi-ters, listen, suppose you interact with the titanium physicist, a little bit more if you would like to keep track of us why not follow us on Twitter at @titaniumphysics or joint our Facebook group. If you would like to hang out with us and socialize why not join our online forum or if you would like to send me an email directly or to ask a question or propose a topic you can email me at barn@titaniumphysics.com. Let's suppose you want to listen to us more conveniently if you've got and iPod or an iPad you can try subscribing to our show on the podcast app. While you're there write us a review. Your reviews determine our ranking on the podcast app which in turn determines how many new listeners discover our show. If you have a Zune or a BlackBerry you can subscribe to our show on those doodads as well or you can download the Stitcher radio app which will let you subscribe to listen to all of your favorite podcasts. You can download the Stitcher app for free onto your iPhone, Android phone, Kindle fire or other devices. Stitcher is convenient because it lets you subscribe to your favorite podcast then listen to them without working. For all of this information and more visit hour website at www.titaniumphysics.com. The titanium physicist podcasts is a member of the BrachioMedia. If you enjoyed our show you might also enjoy Science Sort Of or the Weekly Weinersmith where Kelly and Zack Weinersmith so check them out. The intro music is by Ted Leo and the Pharmacists and the end music is by John Vanderslice. Good day my friends and remember to keep science in your hearts.

[38:03]

Tia: Hey can we do that with the lottery?

Ben: Yeah, well we do, I mean…

Crosstalk…

Tia: Can you make me live that long so I can win the lottery?

Ben: I think you lose money if you do that. It's like playing roulette by playing it over and over and over and over until you hit. You can't get money out of the lottery.

Justin: If they probably designed the lottery, that's true even if you bought all the tickets buying all the tickets will cost you more money then you would get from winning. But people and economists I believe remember where this was at somewhere, maybe it was North Carolina, at some point in the last 10 or 20 years some economists figured out that a lottery in some state, I think it was $15 million or something, was actually, the lottery prize was actually bigger than the cost of buying all the tickets so they got a bunch of investors and they bought all the tickets and then they had some snafus along the way… (bad audio) actually buy millions of lottery tickets but they managed to buy all the tickets for like a seven or… (bad audio) made million dollars off of it guaranteed basically. That was a poor design on the part of whoever designed the lottery I don't think most lotteries are like that.

Ben: Yeah, how did that work it was like it was like a buy 10 get one free deal or something. Was that it?

Justin: I don't remember but there was something weird that allowed them to do that.

[39:53]

Justin: So, with that in mind from what I've heard half lives seem to be pretty on the money like you can say like this has a half life of two years or something like that is that always going to be a constant considering the fact that quantum tunneling is such a rare occurrence and almost random in its nature.

Henry: Well if you think about the number of atoms in you know like a kilogram of uranium you can imagine doing this you know with coins. You know if you do it with like 10 coins, yeah you're going to have fluctuations interns of how big you actually measure the half-life to be. But when you do it with a trillion trillion coins all of that's going to get smoothed it out just by the large numbers.

Justin: Yeah, so even though it's sort of random in nature, seemingly, as you back out more and more you get sort of an almost even constant, even though within the constant there is so much irregularity.

Henry: If you've waited long enough and there were only a handful of the atoms left, then you might actually say, that, you wouldn't really be able to define half-life anymore in the same way because you would start to see the probabilistic effects. But yeah, it's like if you flip a million coins you're going to get pretty close to half of them being heads and half of them being tails. If you flip one coin you're definitely not going to get half of them heads and half of them tails. It's either going to be heads or it's going to be tails.

Justin: Right

[41:30]

Tia: Yeah, I helped make these pictures when I was an undergrad. I followed around this oh so much wiser grad student and he was working on one of these, he had this giant, it looks like a small submarine. It was a vacuum chamber and inside there was so little there, there was less there than there is an outer space. And so inside here he had his surface that he was scanning and he had this little tip and I actually got to help him make those little tips, you blow little bubbles of acid and then you dip this wire into the bubble and it makes this very fine point.

Justin: So it's tapered and sharp, basically it's the tip is about the size of and atom.

Tia: Yeah, the good ones are. The bad tips we had to throw away. Yeah, there’s a lot of those too.

Justin: How do you know when, when you're like okay this is good enough? When you're talking about something that's like you know one billionth of a millimeter or something?

Tia: So these guys, these other physicists on the show are theorists, I am an experimentalist. The way I know it's good enough as I try to take data with it and if the data is no good then I use a different tip.

[43:25]

Ben: Let’s talk about wires first because it's so stupid and then…

Tia: I like it…

Ben: And then we'll talk about scanning tunneling microscopes okay?

Henry: Alright.

Justin: I know nothing about this so I am interested in hearing it as well.

Ben: Okay so, so the following facts I am not willing to put my life's savings down on being true. I heard about this as an undergraduate and on the internet today I confirmed it on the internet from another undergraduate textbook but that's the only place that I have heard of it happening. But, apparently, okay, so copper it's what you make your wires out of let's say you want to splice two copper wires together Justin, what do you do?

Justin: You, I suppose you fray the ends of the wire and then you would um sort of turn them into each other and then tape it up again or something.

Ben: Yeah, yeah, you twist them together right.

Justin: Yeah.

Ben: So the idea here is the copper is a good conductor, you press two copper pieces together and then the electrons will flow from one to the other, kay. Here's the thing, as soon as you strip the copper it stops being shiny immediately, essentially, copper oxide forms on the outside of it. Copper oxide is a really good resistor, it's a bad conductor. Electrons to flow through very easily okay. So electrons move through copper like a fish through water but not so much through this oxide. And so when you twist these two copper leads together you are essentially making a sandwich and you've got copper as the bread and then this bad conductor in between. So, apparently the deal is, that electrons, if you want to pass a signal through those, if you want to shoot electrons down one copper wire and then come out the other, sometimes they tunnel through that barrier. So, the moral of the story is even though tunneling is crazy quantum phenomena sometimes you can still see them on kind of household levels it doesn't just happen inside the sun and inside Godzilla.

Justin: Did the textbook tell you how much of an affect this actually is, like how much the effect is like how much resistance there is, like how much tunneling reduces the resistance…

Ben: Yeah, I think there was something like, I don't know, I think it threw out, there was like a 10 electron volt barrier or something like that so unless you had 10 volts or something going through the wire, classically you shouldn't be able to get a current through it. But what happens is at lower voltages like 7 V or something you could still get current passing through the wire, it just has to tunnel through this connection. So you can still get a signal through the wire even though you know you made a pretty crappy connection.

Tia: That's super cool. So I should make crappy wires all the time in the lab.

Ben: I know. I had no idea it was so crappy.

Henry: If it's actually true I'm amazed.

Justin: So is like the second that a copper wire is exposed to air it gets oxidized to the point that it's kind of useless and it's completely dependent on this quantum tunneling just a function is the argument?

Ben: Kind of. Kind of. So we've been talking about potential barriers like a kid riding over a hill with his bike. So if you put enough voltage through the wire it's like a kid on the motor bike or on a rocket bike it doesn't matter what the hill is he will just zip over the hills. So if you put enough voltage to the wire it doesn't matter if the connection is crappy. It's kind of like how if you take high enough voltage you can get like an arc through something. Like with high enough voltage anything will break down but at lower voltages than should be classically possible, you can still get electrons passing through, it's just that they tunnel through. So it's not entirely useless I think at normal operating voltages things usually pass through but maybe at the level of electronics you know like wristwatches or something it wouldn't work except for tunneling.

Justin: Wow.

[48:35]

Henry: Well I have another example of a barrier which is it's kind of maybe, can be a transition into tunneling. I think we're probably all familiar with when you're underwater or when you look at a fish tank sometimes there is that point to where instead of seeing through the glass or through the surface of the water you'll see a reflection of everything else on the other side and this is called total internal reflection. What it means is that if you get close enough to one of the sides of glass on a fish tank the light, when it hits that glass, it all bounces back to you and you don't see anything from the other side. So the interesting thing is, of course is that light is an electromagnetic wave and so this electromagnetic wave doesn't just stop instantly when it hits the edge of the glass and reflects to you. It actually falls off a little bit, decays. The wave kind of waves until he gets to the glass and bounces off but it waves a little bit into the glass as well and that falls off.

Tia: Evanescent waves.

Henry: Yes, exactly. It falls off very quickly, like an exponential. And so that's a situation where a barrier, that glass is thick enough that the wave can't get through it. But what it turns out that if you actually make the glass thin enough and have say more water on the other side then in a situation where the light would have reflected off of the glass initially if you add water to the other side and make the glass thin enough, that little bit of electromagnetic field that was falling off and decaying, by the time it gets to the other side of the glass it hasn't decayed enough to not do anything, so it actually continues on that side as well and you get the light will also go through that side as well. It's called frustrated total internal reflection. The reflection doesn't actually happen as much as it would otherwise because some of the light can get through and it does in many ways just tunnel through the glass.