Episode 4: The Solar Neutrino Problem
Physicists: Jocelyn Read, David Tsang
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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 which lives within me, a burning desire to share these great ideas with the people around me. And so, I have assembled a team of some of the greatest, most lucid, most creative minds, I have encountered in my travels and I call them my Titanium Physicists. You're listening to the Titanium Physicists Podcast and I'm Ben Tippett. And now allez physique!

[1:49]

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids through a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed - you call
It wonderful; I call it crass.

Ben: This poem by called Cosmic Gall by John Updike describes the loneliest and subtlest of all the elementary particles. The neutrino. A neutrino is like a penny. Any time a nuclear transaction occurs they get generated and then they just float around and disappear and never get used again. So, the nuclear fission occurring at the heart of the sun, the process which generates all the light and heat that the sun radiates also produces a tide of neutrinos that washes out into the universe in a steady stream. In fact, 2% of the energy generated by the sun comes out in the form of neutrinos. Models of the sun which are based on nuclear physics predict that 65 billion of those neutrinos pass through an are the size of a stamp every second on Earth. And not just stamps, they travel through everything. In the 1960s Ray Davis set-up the Homestake experiment in the Homestake gold mine in South Dakota. He took a 100,000 gallon tank of dry cleaning fluid about a mile underground to shield it from the radiation coming from space. He used dry cleaning fluid because the chlorine atoms in it would turn into argon if a neutrino hit it in just the right way. The argon atoms could then be gathered and counted over time and the rate at which they accumulate could tell us the rate at which neutrinos are generated in the sun.

Neutrinos are so subtle that of the quadrillion neutrinos that pass through the tank per day, only one of the chlorine atoms will get turned into argon. So, here's the thing. The experiment ran for 24 years, continuously and the results were astounding. The Homestake experiment told us that only 1/3 of the expected neutrinos were actually passing through the tank. So, either nuclear physics was wrong about what was going on in the sun or the fission process in the sun had shut down. Or, something very strange was happening to the neutrinos in transit. This problem is referred to as the solar neutrino problem and it's wonderful because when I was an undergraduate taking particle physics courses it was an unresolved mystery. Nobody knew why it was happening. But, by the time I had gotten my degree we'd found the answer. So, today we're going to be talking about the solar neutrino problem. Our guest today is Amy Pollien. She's an artist and an apiarist who lives on Mount Desert Island in Maine. Amy started printmaking and industrial design at the Philadelphia College of Art. She has exhibited at the Philadelphia Sketch Club, Rutgers University and Center for Maine Contemporary Art among others. And I'm a big fan of her work. A lot of it seems to focus on using pastels to paint still life's and architectural landscapes of scenes in Maine. I realize that this is a physics podcast and not a podcast about art but I'm a big fan of Amy's work and I just like to say that it breathes light. So, check it out. There will be links to her blog from website. So, Amy, since you're a master of capturing light, I've chosen a topic for you today concerning a problem with capturing neutrinos.

Amy: Thank you for your invitation and I have to tell you that the solar neutrino problem actually has deep emotional significance for me. When I was in high school I was selected as a small group of students who were allowed to go to the Talcott Mountain Science Center in central Connecticut to rub shoulders with scientists and their equipment. And it was fascinating. We did mostly geology but they had telescopes and one day our intern, who's name was Wallace, came up to us and said, let's go check out the telescopes. And we said but Wallace, it's daytime and we can't see stars. And he said but you can look at one star. You can look at Sol and you should because the sun is going out. And we said, what?! He said yeah, there's this thing going on called the Homestake experiment which has found that the sun is no longer putting out the number of neutrinos. They're all disappearing. So, the fission process of the sun has shut down. We just don't know about it yet because of the tremendous distances involved. We were horrified. We studied the sun very carefully that day and many of us went home in tears. And when I got home I realized science was very powerful and I should probably go to art school. But, the resolution of the story is that we went back two days later and Wallace wasn't there. I guess a couple of the parents had gotten together and done something with Wallace and I sincerely hope he was hazing us but if he did go on to physics, probably someone has offed him by this point, who had to work with him. And that's why I know what the solar neutrino problem is sort of about and why I'm happy to hear that it has been resolved.

[7:00]

Ben: So, to put your mind to rest I've got together some of my finest Titanium Physicists. Arise Dr. David Tsang!

Dave: Whhhaaahhaaahaaa!

Ben: Very good. Dr. Dave was an undergraduate with me at UBC. He did his PdD and Masters at Cornell. He's currently at CalTech working as a postdoc astrophysicist. Now, arise Dr. Jocelyn Read!

Jocelyn: WWWWhhhhhhhhaaaaarrrrrrrr!

Ben: Dr. Jocelyn did her undergraduate at UBC and her PhD at the University of Wisconsin, Milwaukee. She's currently at the University of Mississippi working on neutron stars. Alright Amy, this was a fantastic introduction. I can't believe you were told as a child that the sun was going out.

Amy: They had proof.

Ben: That's amazing. Okay, So, let's start our discussion by talking about how we know what goes on in the sun. So, here's a brief tour of the sun I put together. So, let's say you get dropped off at the edge of the sun and you get your snorkel gear and we're going to dive through the sun.

Amy: Does it really have a surface?

Jocelyn: In the same kind of the way that gas giants like Jupiter do. It suddenly gets a lot thinner very quickly. So, it's not like a hard surface but it's the end of the density of the sun.

Amy: Cool.

Ben: So, we start off in the photosphere so that's about a hundred kilometers thick. Keep in mind that the sun, from the edge to the middle, is 1.4 million kilometers. So, the first 100 kilometers, it's kind of opaque, bright gas. This is called the photosphere. This is where all of the light that we see, all of the photons are generated. So that's where they kind of where the put the shine on the energy and send it out into the universe. The next 200,000 kilometers, so, about a 7th of the way down, is called the convection zone. So, you know when you take a pot of water and put it on an element? How you get these bubbles of heat rising up from the bottom? Those are convection bubbles and those happen inside the sun too. So, big bubbles of hot gas rise up from below. Three quarters of the way down you reach the core. So, you tunnel down and get into the middle, and this is the area where all of the nuclear fusion happens. So, right now the sun is undergoing something called hydrogen burning. So, all of the hydrogen atoms in the core, because the core is so hot and dense, they are being turned into helium atoms. And the process of this fusion generates a lot of heat. Ah, so the trick is that in going from a hydrogen atom to a helium atom you get a lot of protons getting turned into neutrons. So, you've heard of protons and neutrons, right?

Amy: Yes.

Ben: Okay, every nucleus is composed of protons and neutrons. Kids learn that there are three fundamental particles to an atom. There are electrons, protons and neutrons. I bet you didn't know though that a neutron is just what happens when you take a proton and shove an electron in.

Amy: Ha!

Ben: Isn't that crazy.

Amy: I've never heard it look that way before, said that way before.

Ben: Well, that's essentially what happens. You take a proton and if you shove an electron in hard enough it will turn into a neutron. And the way we discovered this has to do with the history of radiation. There is a process called beta decay. So, this is Rutherford. So, back in the day there were three different kinds of particles that were emitted from radioactive elements. So, there are alpha, beta and gamma type radiation. So, alpha rays are...

Dave: An alpha particle is a helium nucleus.

Ben: Oh, right! That's it! And then a beta particle is an electron and a gamma particle is, essentially, a little photon. A little speck of light that comes out as a product from nuclear decay. So, Rutherford had sorted these out back at the turn of the century and that's where this particular process gets its name. So, there's a type of reaction that happens inside the nuclei called beta decay. And that's when a neutron decides to give up the ghost and shoots off a proton and an electron. It happens a lot in nuclear fission. Ah, but one consequence of this decay, when a neutron turns into a proton and an electron is that it also shoots off this other type of particle called a neutrino.

Jocelyn: And that's how they figured out, or that's how ah, Pauli, it was Pauli, right? That proposed neutrinos? Yeah, that's how he, he was trying to explain why, when these electrons got shot out, or these beta particles, got shot out, they weren't all at the same energy. The way, if it was just a simple reaction, just from one thing to another thing, it would be. But they got spit out in a whole spectrum of energies which meant that something was taking away some of the energy and smearing out the range. And that mysterious something was what he actually called a neutron at the time.

Dave: In order to make the accounting work he had to propose this new particle.

Ben: That's right. So there was a new degree of freedom somewhere that was making these other energy distributions continuous.

Amy: Huh.

[11:55]

Ben: So, this other neutron, it was called, they went up and asked the great physicist, Fermi, what the difference between Pauli's neutron and the regular neutron was, once they'd sorted everything out and Fermi said, famously, Ah, the neutron, it's a small neutron, it's a neutrino. And that's why we call them neutrinos.

Dave: It's like when I don't have a mushroom.

Ben: Okay.

Jocelyn: Okay, so yeah, they knew there were these little neutral things and then they discovered these huge big, proton mass sized neutron things in the nucleus and so, they were like, okay, well we've got a big a big neutron and we've got a little neutrino...

Ben: The idea here is that the neutrino is an elementary particle that's kind of required to trigger this beta decay. Okay, so, whenever you have beta decay there is a neutrino in there somewhere. So, in the center of the sun there is protons turning into neutrons and in the process a bunch of these neutrinos are produced. And the kicker is that because the sun is made of this opaque, dense, charged gas it takes a long time for a proton to make it from the center of the sun where it's generated out to the edge. Because every time it gets emitted by one particle it immediately gets absorbed by another particle. So, it bounces from particle to particle as it slowly makes its way out. A little bit of energy takes a 100,000 years to make it from the core of the sun out to the edge. But, these neutrinos are so weakly interacting they just pass...

Jocelyn: Yeah, that's where we have to correct the poem that we started out with. Because they say the neutrinos do not interact at all but they actually only interact with the weak force.

Ben: Yeah, so I need to stop and put in a little bit of a descriptor here. I say that they are weakly interacting, they literally hardly interact with anything. But, formally, the force they poke other particles with is called the weak force. And it's called the weak force because it's a very weak force that only exists on the inside of nuclei. Okay, back on topic. So, in the center of the sun, where all of these packets of energy, these photons, are made through fusion and also these electron neutrinos, it takes a long time for the photons at the center of the sun to make their way to the edge and out into space. But it hardly takes anytime at all for the neutrino to. And that's because the neutrino not only interacts very weakly but it's also very, very, very, very light. So, historically the neutrino has zero mass. So it's traveling so fast it's traveling almost at the speed of light. In fact, historically, they treated it as if it was traveling at the speed of light. And so it takes almost no time for it to travel from the center of the sun out to the edge, through space, through us, and all the rest. Right? And this is why your friend at the observatory, as a kid...

Amy: This is why Wallace explained to us that the sun's furnace had stopped but we wouldn't see it.

Ben: That's right.

Dave: The neutrino signals...

Jocelyn: The photons are coming out, knocking into other things. and they are taking thousands of years to travel out from the core. But the neutrinos...

Dave: If the sun stopped fusing then it would take a long time for that photon signal to reach us but the neutrino signal would reach us fairly quickly.

Ben: That's right.

Jocelyn: In 8 minutes.

Ben: Kind of like, oh, here's what it's like.

Amy: 8 minutes?

Jocelyn: That's how long it takes something traveling at the speed of light to get from the sun to the earth.

Ben: So, it's like all these photons are trapped in traffic and so they have to wait for the traffic to get through. But neutrinos, it's like they're on bikes so they just go right between everything and it doesn't take them any time at all to get all the way out.

Amy: Okay.

Jocelyn: Bikes that can pass through cars, the best kind of bike.

Amy: Yes.

Laughter.

Ben: Okay. So, the deal is that the solar neutrino problem has been resolved. I told you at the start that there was one of three different possibilities. So, one, it could be the case that for some reason fusion wasn't happening very quickly in the center of the sun and the sun was going out. Or it was possible that our model of particle physics was wrong or a third possibility was that something was happening to the neutrinos as they traveled from the center of the sun to us that diluted their signal. And, in fact, that's what happened. So, there's a nickel mine in Sudbury, Ontario Canada and they built a big neutrino observatory and filled it with heavy water and they used it to resolve the solar neutrino problem. And it turns out that what was happening, was that some of the neutrinos were turning into different types of neutrinos and the Homestake experiment was only testing for one of the three different possible types of neutrinos. And that's why it was getting a signal that was a third as strong as it should have been.

Amy: They only thought there was one type, right?

Jocelyn: No, they knew about the three, by then the weak interaction had pretty much been worked out and they knew that the weak interaction has flavor.

Amy: Oh, flavor?

Jocelyn: Yes.

Ben: Yeah, we need to start talking about flavor.

[16:47]

Dave: So, there are three different types of leptons, or light particles. Like the electron, there's the electron, the muon, and the tauon and each of those is a different flavor of lepton. And for each of those leptons there is an equivalent flavor of neutrino. For the electron there is the electron neutrino, for the muon there is the muon neutrino, for the tauon there is the tauon neutrino.

Ben: So, they're all like electrons only they're heavier. So, the electron has two heavier older brothers and the thing about these heavier older brothers is that they are unstable. Muons decay into electrons, tauons decay into muons and electrons, and then electrons don't decay into anything. But, the kicker is that there are three different flavors to these elementary, super light particles. Lepton means light, right. Light as in, not heavy. Not light as in luminous.

Dave: So, electrons will only interact with electron neutrinos whereas muons will interact with muon neutrinos and tauons will interact with tauon neutrinos.

Jocelyn: We know that if you have a reaction with an an electron involved it produces an electron neutrino but we'd also been producing tauons and muons. Okay, so we'd also been producing in whatever particle accelerator is these heavier types of leptons, so the electrons as well as the muons and the tauons and these heavier ones produce their own kind of neutrino. And then you could see it because then later the neutrino would interact again and if it's just this very short path between one part of a particle chamber and another, something that was produced by an electrony reaction will then be seen in another electrony reaction. So we know that we have these three types of neutrinos, but in the sun, all these reactions that are powering the nuclear fusion in the sun are producing electron neutrinos. So, those are the ones we are looking for.

Ben: Right. So, if you had a neutron and you smacked it with an electron neutrino just the right way you could produce a proton and an electron, or if you smacked the neutron with a muon neutrino, you could make a muon and a proton. Or if you hit it with a tauon neutrino you could make a tauon and a proton.

Amy: Okay, but the Titanium Physicists are getting really deep for a cadmium artist, and so what I think I've got from this is that the earlier experiments only showed about a third of the activity that they should because only about a third of it was the particle they were looking for.

Ben: That's right.

Dave: That's right. And so what happened is that the particles were changing as they traveled from the sun to the earth. So, instead of all...

Amy: Ooooh!

Dave: So, we were only seeing 1/3 of the electron neutrinos that we expected. So, what was happening was that the other 2/3 were changing into other kinds of neutrino. That's a phenomena known as neutrino oscillation.

Amy: Which, why... they had mass.

Crosstalk

Dave: Right, now It's a little bit complicated to explain this but we're going to try...

Jocelyn: Well, we can, we can start off with just the relativistic thing. If something is traveling at the speed of light it's clock is not ticking so it's frozen into whatever state it's in, it can't change into another thing. So, as soon as we have things mixing we know that they have to have some mass.

Amy: Huh.

Ben: So, special relativity tells you that the faster you go relative to me the slower I see time passing for you. Okay, so if you go 3/4 the speed of light, I take a telescope out and look at the watch on your wrist and I see the seconds ticking past very slowly. And then it's limit, once you reach the speed of light, I see time stop for you. This is why it's impossible for somebody with mass to reach the speed of light. Only things without mass can move at the speed of light.

Dave: So, if these neutrinos were massless then we'd never see them oscillate, they'd just stay the same the whole time. But because they are changing then we can presume that they do have mass.

Amy: Okay, that I get.

Jocelyn: And then we can talk a little bit about why them having mass means that they can mix. We start by going back to the uncertainty principle. So, you've heard of that probably at some point?

Amy: Yes.

Jocelyn: So, so this is sort of...

Amy: I have a t-shirt.

Jocelyn: Oh. Yay! This is one of these sort of fundamental properties of quantum mechanics when you stuff described by quantum mechanics you find that you make one type of measurement, say you're trying to measure it's position, and if you know exactly where it's position is you suddenly realize it's got a whole range of possible momentums or velocities and it exists in this sort mix of all those other states. And so, if you know it's position, then you have this whole range of other properties that are sort of fundamentally uncertain and the same way as if you know how fast it's moving then it's got a whole spread of possible positions. And so, what happens with the neutrinos is something, so instead of measuring, say it's position and velocity, you're trying to measure either the neutrino's mass or the neutrino's flavor.

Dave: You could think of this, neutrino oscillations, in the following way. Imagine a fruit salad.

[21:51]

Amy: Okay.

Dave: So, imagine that electrons only like a particular recipe of fruit salad, like say from one particular restaurant and that recipe of fruit salad consists of, you know, 10% kumquats, 30% bananas, and um, what's left, 60% watermelon.

Ben: How about the electron fruit salad.

Dave: The electron fruit salad. Right. And say, muons and tauons prefer their own particular recipes that are different percentages and each of them is a very picky eater, they only like eating that particular type of fruit salad and they won't touch, they don't like eating the other ones.

Ben: Oh, so I was going to say the muon fruit salad has like 25% kumquat, 70% watermelon, 5% banana. So, the same three ingredients but in different proportions.

Dave: Proportions.

Jocelyn: Can I spoil one of the punchlines and say that the different fruits are different masses now?

Dave: That's right, that's what we're getting to. So, now remember that kumquats are much smaller than bananas and are much smaller than watermelons. If you imagine that the reactions in the sun shoot out an electron fruit salad and, or at least they shoot out the fruits that make up the electron fruit salad and they are all moving together. And so, because the watermelon is much more massive than the banana which is much more massive than kumquat, if you remember in quantum mechanics, particles are waves and so you can write down something called the De Broglie frequency so if something has more energy it's a higher frequency so, a watermelon, because it is much more massive moving at the same velocity would have a higher frequency than the banana which has a higher frequency than the kumquat. Does that make sense?

Amy: Yes. I mean, I have the picture.

Ben: There's a bowl of fruit salad that some nuclear reaction threw towards you and each component of the fruit salad is moving with the same velocity but the watermelon component has a different energy and a different De Broglie frequency than the kumquat parts of the fruit salad.

Amy: Right.

Jocelyn: So, the nuclear reaction has basically measured a particular flavor but when it measures that flavor it implies that there's this whole range of masses. There's three different mass states, that it's in a particular probability of being in each of these three and that's the fruit salad that gets sent off. And then, as soon as the neutrino is traveling through space, the way it travels through space it is governed by its mass.

Dave: Right. So, as it's moving towards us through space these waves oscillate around. Now, if all the wavelengths were the same, if all the masses were the same then they would all oscillate together and the proportions of each fruit would remain the same.

Amy: Would be the same. Right.

Dave: At the crest of a wave you can say, at the crest of the watermelon wave, for instance, you'd have a large amount of watermelon. At the bottom of the watermelon wave you'd have less watermelon. So, if they were each the same mass and if they each had the same frequency then as they oscillate they wouldn't change their proportions. But they don't have the same frequency so they get out of phase. So, as they get out of phase the proportions change in this fruit salad recipe. So, if you measure this bowl of fruit salad sometime later you'll have a different proportion of kumquat to banana to watermelon.

Amy: Because the masses are different.

Dave: That's right.

Amy: Okay.

Dave: So, that's how the flavor can change. Cause now you might have a recipe, that say a tauon or a muon would prefer rather than an electron.

Amy: Huh. This is going to be a really great chain of restaurants you guys.

Dave: Now, because these, because these frequencies are different you do get these beat frequencies. Jocelyn, did you have a demonstration?

Jocelyn: Oh gosh yes.

Ben: Oh, yeah, Amy, Do you know about beats? You know about dissonance, right?

Amy: Yes. I know about dissonance.

Ben: When you have two different frequencies that don't quite match up you get beats.

Jocelyn: I'll do an artificial beat frequency imitation so this is just a sketch of, an auditory sketch of beat frequency. So, you'll, this is a kind of thing people do in physics demonstrations a lot. But you have one you know, one tuning fork that's at meeeeeeeee then you have another tuning fork that's at meeeeeee, just slightly different, when you ring them together what you hear is something that's kind of at the average tone I'm really not good with pitch, but it's somewhere in the middle and it fluctuates so it's meeee eeee eeeee eeeee.

Dave: So, what's happening here is as the waves get out of phase they'll eventually come back into phase when they reach the least common multiple of wavelengths.

Amy: Does this happen with any pattern?

Jocelyn: Yeah, you can predict it with, you can do the quantum mechanical calculation. So you say, I start off with my electron neutrino. So, and then that electron neutrino is this percent likely to be this mass, this percent this mass and this percent this mass and then you evolve each of the masses with their mass properties and at each point in the path of the neutrino you can say, okay, I measure flavor here and you see what probability it is. And it will actually go up to almost 100% electron neutrino probability again at particular distances.

[26:54]
Dave: That's right. Because they come back into phase after each of them has gone through an integer number of cycles.

Jocelyn: Yeah, so they have drifted, the three different masses that the electron neutrino is composed of have drifted out of phase but then they all line up again perfectly when the beat sound got loud and it's like, oh, yeah, that's exactly an electron neutrino. And then it will sort of dissolve again as it continues.

Dave: So, that's what we mean by neutrino oscillation, neutrino flavor oscillates away from being the electron fruit salad and then comes back into phase again and becomes an electron fruit salad recipe again at a particular distance.

Amy: Interesting. It's an even better restaurant concept now. Sometimes you get the omelette you want, sometimes you don't.

Ben: It depends on how far from the kitchen you are. Or the washroom. If you sit right next to the washroom it doesn't taste like delicious omelettes at all.

Amy: And the mass of your chosen ingredients.

Dave: And also, we're firing the plates at you at close to the speed of light.

Laughter.

Ben: Okay, so, the theoretical picture we have so far is that in the middle of the sun all of these neutrinos are made as electron neutrinos but then over the course of moving from the sun to us their neutrino flavor oscillates and we might might measure them as an electron neutrino or a tauon neutrino or muon neutrino.

Amy: Right.

Ben: So, one question you might ask is, well why didn't the original experiment pick it up. Why was it 1/3? And the answer is that the neutrinos that are made in the middle of the sun don't have enough energy when they hit a neutron to make the neutron spit out a muon or spit out a tauon. They're only energetic enough if they hit a neutron to make it spit out an electron. So, what this meant was that only 1/3 of the neutrinos once they'd reached earth were energetic enough to cause the neutron to decay.

Amy: So, you're talking about the part where they were counting Argon?

Ben: I'm talking about the part where they were counting argon atoms. So, only 1/3 of them were energetic enough to create argon atoms.

Amy: The rest were just passing through and were not affecting the cleaning fluid.

Ben: That's right. They were too weak to do anything. And so interestingly enough they came up with a new way to measure neutrinos that was very, very sexy. So, there was one of these observatories in Sudbury. So, the deal WA s, several Canadian and international universities collaborated and they built, in essence, it was a giant tub...

Jocelyn: It was a giant sphere of heavy water.

Ben: It was a giant sphere of heavy water. Ah, it was 2 kilometers deep, under a nickel mine, underneath the city of Sudbury in Ontario. And so all of the earth between this detector and the surface would filter out all of the different sources of radiation that might cause triggered events.

Dave: Cosmic rays. It doesn't filter out all of the backgrounds from the radioactive decay in the earth.

Amy: Guys, guys. Guys. Back to the ball.

Ben: Thank you Amy.

Amy: You're welcome.

Laughter.

Ben: Under the earth there's this bottle...

Laughter.

Ben: So, they did something really sexy, they filled it up with heavy water and...

Jocelyn: Someone's doing sound effects? Is this on purpose?

Dave: I'm back to the bottle.

Laughter.

Ben: So, when a neutrino would come it would interact with the water in this giant sphere in one of two different ways. So there was this sphere of super, super pure, heavy water and around it were photomultipliers, very very sensitive, in essence light measuring devices and so...

Amy: Oh, blue light, right?

Ben: Yes! Cherenkov radiation.

Jocelyn: Cherenkov radiation.

Ben: Yes. You've gotten ahead of us! Okay, so...

Amy: It was an art project.

Ben: Oh, fantastic! Ahhh, right, so, I'll have you explain Cherenkov radiation in half a second. So, one of the two processes was called the charged current interaction and that's when a neutrino would come in and hit a neutron and cause it to spit out an electron and a proton. And that electron would be traveling so fast as a result that it would cause Cherenkov radiation because of that nuclear interaction. We would only see the 1/3 interaction because only electron neutrinos could cause that interaction to happen. But the second way any neutrino could interact with this is the system was so pure and so dark that occasionally neutrinos would come in and kick an electron. So, an electron would get in the way of the neutrino and the neutrino would give it a little kick in the direction that the neutrino was going.

Dave: In a specific direction.

Ben: And so, ah it would push it fast enough that you'd get this Cherenkov radiation. So, Amy, what's Cherenkov radiation?

Amy: All I know is that it can be detected as blue spectrum light and that's pretty much it. It's been used to artistic affect and there is actually film of it. I don't know how they did that but I'm curious.

[31:57]
Dave: It's when a particle moves faster than the beautiful light in the material.

Jocelyn: Yeah, because if it's moving faster than the speed of light in that material it's got enough energy to create light particles, to create photons.

Ben: The Cherenkov radiation is kind of like a sound shockwave. You know how a jet makes a sonic boom when it...

Amy: When it breaks the sound barrier.

Ben: That's right. So, there is something equivalent in electromagnetism. We're told that the speed of light is the fastest something can go, but usually when we say that the maximum speed is the speed of light we're referring to the speed of light in a vacuum. So, if you have a transparent material or a medium like a piece of glass or some water, as the light moves through it's actually kind of bouncing around on the atoms as it moves through. And so it moves through at a slower speed than it would through a vacuum. And so there is some finite amount of speed that a photon can move through this block of acrylic or you know, water. And, as a result, you can shoot an electron that moves faster than it through the medium and that causes an electromagnetic shockwave and that shockwave is what we see as Cherenkov radiation.

Amy: That's very cool.

Ben: Incidentally, did you know that Godzilla shoots off Cherenkov radiation? If you watch Godzilla movies...

Amy: No. I did not.

Ben: It's true. When Godzilla goes under water he glows blue from the Cherenkov radiation.

Laughter.

Ben: Right. So there's this big sphere of heavy water deep underground and it was so deep and dark that it when, occasionally, a neutrino would come in and give an electron a little kick the electron would then shoot off some Cherenkov radiation which the photomultipliers placed around the sphere could detect. So, from that we could detect that were coming from the sun, for instance. And we could also count up how many events and...

Jocelyn: And these ones would happen for every flavor of neutrino. It didn't have to be an electron neutrino. So they could detect any other type of neutrinos that were coming from the sun.

Amy: Okay.

Ben: You can sleep well tonight because there were the proper number of neutrinos predicted coming through, so there wasn't a deficit.

Amy: Ahhh, okay.

Dave: So, the sun is just fine.

Amy: Ahh, alright, okay.

Ben: So, the Sudbury Neutrino Observatory demonstrated that our sun is producing the right number of neutrinos and it demonstrated two things. Firstly, that neutrino flavors mix which is crazy and second that neutrinos have mass. Because, the only mechanism we could think of for them to mix this way is if they have mass.

Amy: Right. Okay. Decades of worry.

Dave: And they are different mass states.

Ben: Right.

Dave: Because if they were the same then they would all oscillate together.

Ben: Right.

Dave: Wouldn't have a, the recipe, the fruit salad recipe would be the same.

Amy: So really the entire conundrum, the solar neutrino problem, as sort of started let's say by the Homestake experiment was an issue of really of measurement.

Dave: Of accounting, yeah.

Amy: Yeah.

Ben: So there was a phenomena occurring that we hadn't accounted for that was the reason that the Homestake experiment wasn't working. Because if the neutrinos hadn't been changing flavors midway through the Homestake experiment would have shown the right number.

Amy: Huh.

Jocelyn: So, this is, you know, full on physics of some weird measurement happens and then everyone looks at the theory and tries to figure out what could explain that and thinks of the worst case scenarios and scares children with it, as they do. And then ah, and then someone said oh no, no guys it's cool, it's cool, I just need to add this other factor in.

Dave: We think this is what's happening and then someone else goes and measures that and sees that is indeed what is happening and then everything is cool.

Amy: And Wallace is somewhere measuring permafrost in Antarctica, perhaps.

Dave: Possibly.

Ben: I think we're about at our time limit.

Amy: I think you pretty much explained to me what the problem was in the solar neutrino problem...

[35:41]

Ben: Right.

Amy: And why Wallace's explanation back in the early 70's was deficient. Thank you very much, that was, ah

Dave: Hopefully we were sufficiently clear.

Amy: It was, it was. It was hard slogging for a little bit but I'm trying to model myself as a neutrino and just flow through it.

Crosstalk.

Ben: Okay, I guess if there aren't any more questions I better close the show. Thank you Jocelyn and Dave. You've pleased me with your efforts. Your efforts have born fruit and that fruit is sweet. Jocelyn, here is your kumquat. And Dave, here is your watermelon. Enjoy your fruit. Alright, I'd like to thank my guest, Amy Pollien. You've been lots of fun.

Amy: Thank you for having me on the show Benjamin.

Ben: Well, thank you for keeping everything clear for everybody.

Ben: So, if you want to email us you can email us at barn@titaniumphysics.com or you can follow us on Twitter at @titaniumphysics. You can visit our website at www.titaniumphysics.com or you can look for us on Facebook. If you have a question you would like my Titanium Physicists to address email your questions to tiphyter@titatiumphysics.com and if you are a physicist and would like to become one of my Titanium Physicists email physics@titaniumphysics.com we're always recruiting. The Titanium Physicist podcast is a member of the BrachioMedia. If you've enjoyed our show you might also enjoy Science Sort Of or the Weekly Weinersmith, please 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.

[38:22]

Ben: Okay.

Dave: You have a very good radio voice.

Amy: Thank you.

Ben: You could be on NPR...

Dave: You totally sound like NPR.

Ben: Yeah.

Amy: Actually, in the 70s I worked my way through college being the person who says in case of fire please exit to the north stairwell... Please dial 2 for English...

Laughter

Jocelyn: Oh my gosh, that's so great!

Amy: Yup.