Episode 70: Muon, science cat, muon
Physicists: Ryan Martin, Dianna Cowern

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 in 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!

[1:49]

Ben: Physicists are famous for quips. Or, rather, I should say, among physicists, some events are remembered in terms of a physicist who was there at the time who said something quipy. You probably haven't heard most of them but you are surely familiar with a few of them. On the advent of our interpreting quantum mechanics Albert Einstein was corresponding with Max Born and famously quipped that the Copenhagen interpretation of quantum mechanics was surely wrong because, "God does not play dice". Or, when the first atomic bomb was tested in 1945 in New Mexico, the theoretical physicist and director of the Manhattan Project, J. Robert Oppenheimer was awed at the power his efforts had placed into our hands and he quoted from the Bhagavad Gita. He said, "Now I am become death, the destroyer of worlds." One of my favorite quips is from the advent of modern particle physics. Back in the early 1930s we thought that we had all the particles figured out. Now, the story is a little different than the one you learnt in high school because of quantum mechanics. But, the actors are all still the same. Everything was made out of three elementary particles. There's a proton and a neutron and they live together inside of a nucleus and then there are electrons who live outside running around like a dog in the yard. At this time we figured that that was all there was. Some theoretical work had been done on the possibility of other short-lived particles that might have to do with radioactive decay but no one had ever seen them. And in the mid-1930s we detected something new. A new particle, different from the other three. Different in character, just different. We called it a muon and it upset the applecart. In this context, this world changing context, where suddenly everything we knew about matter in the universe suddenly became superficial and we were forced to consider new depths of possibility, Isidor Issac Rabi, and he will be known forever for having said it, he said "Who ordered that?" Like everyone was sitting around eating take-out Chinese food and there was an extra container of rice. Who ordered that? I'm not sure if it's a privilege to live in an era of great discovery. Like maybe discovery is the wrong word. Muons weren't discovered the way the secret to making gunpowder or ice cream were discovered. They were always around us, just unrecognized. I could only wonder at whether these particle physicists felt the floor falling out from under them as they discovered that the story was much, much more complicated and harder to understand than they had always assumed. People are emotionally invested in things they think are certain. What's a person to do? The same thing you've always done. You don't turn your back on the truth. And you do good work. Seek reliable data. Seek reliable explanations. Build a new standard model. Teach yourself. Teach your students. Move forward. In the 80 years which followed we discovered a whole new system of fundamental particles. Six quarks, six anti-quarks, six types of leptons and six anti-leptons and force carrying bosons as well. The muon was just the tip of the iceberg but the muon was the first. Who ordered that indeed. Today on the Titanium Physicists Podcast we're going to talk about the particle that upset the applecart, the stablest of the unstable particles, the sibling of the electron, it's the muon. And our guest today has become a renowned author in recent years, publishing essays and short stories in all manner of publication from the *Drabblecast* to *Mashable* to the *Boston Globe.* But her ambitious prose came to my attention with a debut novella called *River of Teeth*, an alternate history story about bloodthirsty feral hippopotamae wondering the Mississippi and the people hired to hunt them. It's available now on Amazon for pre-order. Welcome to the show Sarah Gailey!

Sarah: Hi!!!

Ben: Hi! So, Sarah, for you I have assembled two old friends. Arise Ryan Martin. Dr. Ryan did his PhD at Queens University and then after postdoc at Lawrence Berkeley National Laboratory, he is currently an assistant professor in the Physics Department at Queens University where he studies neutrinos. Now, arise Dianna Cowern!

Dianna: Wooooooo! Yeah!!

Ben: Diana Cowern is one of the world's leading physics communicators. She did her physics undergraduate degree at MIT and you probably know her better as the host of the very popular Physics Girl YouTube channel. Alright everybody, let's talk about muons.

Dianna: Muons!! Yeah, so the first bit about a muon is like, what is a muon. Ben gave that wonderful introduction and gave the muon the glory it deserves. Yeah, a muon is a very small particle so it's like an electron or a proton you know in the sense that they are all particles. But, it is more like an electron in the sense that it is what's known as an elementary or a fundamental particle.

[6:45]

That means that, as far as we know, it is, like, the bottom, it's the base, it's not made up of anything else, it is fundamental. It has a negative charge, so, back in middle school when you learned about, you know, negative charge and positive charge, like the electron has a negative charge, proton has a positive charge, and they attract and so forth. Um, the muon has a negative charge. So, it's very much like an electron, it has a negative charge, it is a fundamental particle like an electron but it is much more massive. It's like really heavy compared to an electron.

Sarah: You know, I thought you said it is small?

Dianna: It is very small. It is massive.

Sarah: Oh, it's like, dense.

Ben: Okay, yeah, that's a great question. Because the answer yes would be intuitively correct but electrons and muons are both point-like particles and that means that all of their mass, instead of being distributed over an object with volume, like a cannonball right? You can say that this cannonball is heavier than this softball because its made of denser material, right? Well, in this case all of the mass is concentrated to a single point in both the electron and the muon and so the mass is fundamental. Ah, every muon has the same amount of mass and ah, that mass doesn't come from it being made of anything else. So, like some things, like, protons. Protons are made of other things so when you're in elementary school you learn that protons and neutrons are fundamental, right?

Sarah: Yes

Ben: But, they're not. They're made of other things. If you take a beam, of, like, electrons or some other probing particle and you shoot them at a proton fast enough to...

Sarah: Like you do.

Ben: Like, get in there and really probe the inner structure, you see that the inside of every proton are three of something. And you don't know what they are. It turns out they are quarks. It's just, there's another basement to the fundamental particle thing when it comes to protons and neutrons, they're made of a smaller, fundamental particle.

Sarah: Right. As in all things, my elementary school teacher lied to me.

Ben: Well, they didn't lie to you about the electron. The electron is a fundamental particle. It's not made of anything else. Ah, and neither is the muon. In fact, the electron and the muon share a lot of things. They spin the same way. They have the same electric charge. You know, in terms of mathematics they are very similar except for the difference that the muon is very heavy. It's got a lot of mass. Where, it's two hundred times, give or take, 207ish times heavier than an electron. So, it's much more massive in spite of the fact that 1, it's point like so we can't talk about its density. We can't attribute that increase in mass to anything else and 2, ah, it looks electrony.

Dianna: Yeah, I want to add in there, like Sarah, when you said, like, it's dense, I was like, that is such a good word. But then you broke me as a physicist, because, I like, I froze, like a cat, that has a brain freeze. Because, I was thinking like, yes, like, it has a lot of mass in a very small volume. So, that is the definition of dense but, like Ben said, it's a point particle, it doesn't have a volume as far as we know. It's so small as to not even take up any space but yet, it has mass. Oh my god, such is the weirdness of particles.

Sarah: I'm so proud of myself. I make it a point of pride to try and break at least one physicist everyday and I was worried I wasn't going to manage to fit it in today with my very busy schedule but I still pulled through.

Dianna: Congratulations. I'm happy to be the one you broke on this Wednesday evening.

Ryan: There's a cartoon explanation of mass, right. So, I'll just sketch it out. The Higgs Boson, this famous thing that's always in the news, at least if you're a physicist. It tries to explain how the particles have different masses and the way they picture mass is how much the various particles like to interact with this Higgs Boson which is another particle. And so the cartoonish explanation is, if you imagine a person that is trying to cross the room. So, it's a party and you have a bunch of people in the room and the person wants to cross the room. So, maybe the first person that comes in is a physicist and they're not very popular, it's very easy for them to cross the room because nobody stops to talk to them. The next person that comes in is a muon, they're very popular and so they try to cross the room. But every time they take a step more people want to talk to them. So it takes them a long time to cross the room because they are so popular, all these people want to talk to them. So, even though the two people are the same size they both have different affinities for other people or Higgs Bosons and that's sort of what the mass is. And so, the muon and the electron are both infinitely small but the muon is more massive so, that mass is felt as its desire to interact with the Higgs Bosons that are everywhere through space. That would be the cartoonish way to explain it.

[11:43]

Dianna: The muon is, like, the beginning of a world of particle physics where, most people, you learn about protons and electrons and neutrons at some point in their science classes and then that's it. That's like, that's what all matter is made of, that's all you need to know. But, there's like all these other particles. So many different kinds of particles and muons were one of the first ones discovered besides protons, neutrons and electrons. So, like, muons were like, super exciting to physicists because they were like oh my god, this whole world is opening up into other kinds of particles, maybe other kinds of matter, maybe other kinds of, you know, things that we've never ever seen before and muons were one of the first discovered.

Sarah: So, here's my confusion. I was under the impression that science was completely static and we had discovered everything that we were ever going to discover and will ever discover as of, like, 1934.

Ben: Whoever told you that? That was back before, that was before they discovered a muon.

Dianna: Yeah.

Ben: Literally on the cusp of...

Sarah: Do you mean to tell me that there's more science.

Ben: Yes.

Sarah: Surely not.

Dianna: I love that you picked 1934 because it's like, right before muons were discovered.

Sarah: I don't even have the muon Wikipedia page opened. I should do that so that I can say more clever things but I'm not going to.

Ben: Okay, so, to summarize. Muons are like electrons. They are, essentially, the same thing except for a few key differences. One of them is how much more mass it has. And Ryan says that the reason they have more mass is because they interact with the Higgs Field in a little bit different way. So, the Higgs Field is this field that they discovered that's there to kind of explain why things like electrons have different amounts of mass than things like muons. So, the deal is that muons hug Higgs Fields more than...

Sarah: I'm sorry, did you say that they hug...

Ben: Yeah sure.

Sarah: the Higgs Field?

Ben: They interact with it more. They cuddle to it more, they stick to it more.

Sarah: That's so friendly, like, they're just hugging. They're all best friends comforting each other through hard times, that's nice, that's nice. I like it.

Ben: That's right. They have more inertia as a result of this. Okay, so, there's another big way that they're not like electrons. Because if they were like electrons in every way, to be honest, we would see them everywhere. Like, we detected electrons, why did it take until 1930ish for us to detect muons? And the reason is because muons fall apart. That's not quite the right word. They don't fall apart because they're not made of anything but they are what's called in the particle physics community, unstable. Which means that they...

Dianna: They fall apart in, like, the emotional way.

Sarah: They just have a lot going along right now and they need some space and they just need you to understand that they might have to cancel on you last minute because, like, things are intense and sometimes they need to take a night for themselves.

Ben: Muons are a little flakey.

Dianna: Exactly.

Ben: Okay. And sometimes they just spontaneously turn into a bunch of other particles. And then they stop being muons and they start being electrons and neutrinos.

Sarah: I mean, doesn't that happen to us all from time to time?

Ben: It doesn't happen to electrons or neutrinos. They mostly stay electrons and neutrinos.

Dianna: The're are a few that refuse to change.

Ben: It's like how everybody eventually turns into a very angry old person who refuses to change. The deal is that there's just kind of an echelon of different particles. The idea is that once the muon changes into a bunch of neutrinos and electron they kind of go their own separate way and they won't turn back into a muon. So, you know, muons get generated in our atmosphere, we'll talk about that in a little bit. But essentially that's what they first detected muons, in that circumstance. And they get created, they last quite awhile for a particle. Their mean lifetime is something like 2 microseconds which in particle terms is forever. So, they stick around for 2 microseconds and then on average they'll just spontaneously turn into a bunch of electrons and tiny little neutrinos and that's why we don't see them everywhere. Because all the ones that were muons, in that time, turned into electrons.

Sarah: Can one of you tell me, what fraction of second a micro second is?

Ryan: One millionth.

Sarah: Okay, yeah, so, that's a super long time. Just like, two of those?

Ben: Yeah.

Dianna: Wow. Not one, but two.

Laughter.

Dianna: It's interesting to me that there are particles that decay so much faster than two millionths of a second. In like, in particle world 2 millionth of a second is a really long time.

Sarah: What about the decay time of an electron or a proton, do those decay, ever?

Ryan: That's an interesting question actually. The decay of a proton, so on the outer scale of things, there's a lot of experiments trying to see if protons do decay. Um, that's like one of the big, holy grails of particle physics, is to observe a proton decay. So, they have these very large experiments where they have a lot of protons and they just look at them for years.

[16:43]

Sarah: Oh my gosh.

Ryan: And see if... decays.

Dianna: Well, if they don't decay, like, if a proton is really, really stable and they never decay then that is the longest most boring experiment ever possibly conducted.

Ryan: Yeah, except those experiments have, fortuitous, they have discovered other things. There was a series of proton decay experiments in the 80s. They were, they had a lot of protons, by just having a large amount of water, any matter has protons in it really. And while they were observing this water looking for a little flash of light from a proton decay, all of the sudden several of these experiments around the world saw multiple flashes of light all at the same time. And it turns out that all those flashes of light were from neutrinos, a different particle coming from a super nova in a different galaxy. So, they were trying to observe proton decay and sort of serendipitously they, effectively made a telescope to look in a different galaxy and see a star explode. So, that's kind of cool.

Sarah: Whaaaaaaaaaaaaaaaaat?!

Dianna: Yeah. I feel like that's how physics always goes. There you go Sarah. So, there has been physics done since the 30s.

Ryan: So, also, there's a whole spectrum, right. So things like the proton, they might never decay.

Sarah: What about the electron?

Ryan: Ah, I don't think the electron decays either. Neutrons decay, actually, pretty quickly.

Ben: The average neutron that's outside of a nucleus, will turn into other particles in about 14 minutes.

Dianna: Sorry, I have a question. Is decay anything confusing to you or boring to you?

Sarah: Um, no I, mean, I write science fiction fantasy and horror and as a horror writer I am a huge fan of all forms of decay.

Dianna: Ooooooh, I see. Yeah, I feel like physicists love to commandeer words and use them in a very specific way. Like decay as rotting flesh is very different from decay as a particle.

Sarah: Well, I just picture the particle kind of shambling along and limbs are falling off and then its turning into a skeleton and then that's falling apart and that's kind of the mental image that I work with. Which is way more fun than any other one where you are just turning into an isotope.

Ben: That's great because it's an interesting contrast. You were like, hey, when I imagine decay I imagine something falling apart and turning into ah, bones and globs of meat and stuff, right? Um, in some sense, when we're talking about things decaying we're imagining that, ah, they are turning into their constituent parts. So, instead of being meat on a bone, it's now a skeleton without any meat on it and then the meat is somewhere else, right?

Sarah: Right.

Ben: So, um, that's not how particle physics works. And it's not how particle physics works in a really interesting way. You can make particles out of other particles.

Sarah: It's like a zombie decays into a vampire.

Laughter.

Sarah: Okay, we need to have a conversation about zombies and vampires on my podcast.

Ben: It's like a zombie decays into a small vampire and also two, I don't know, ah, two wolfmen?

Sarah: Yeah.

Ryan: Baby werewolves.

Ben: Yeah, two baby werewolves and...

Sarah: You guys have got your hierarchy of monsters of all wrong.

Laughter.

Dianna: We're physicists, okay?

Ben: The thing about particle physics is that the processes that happen are entirely statistical. Ah, there is some probability that something will turn into something else and it, there are conversation laws at play that dictate what things can turn into other things. So, for instance, we talked about how neutrons decay. If a neutron decays it's going to turn into, ah, a proton and an electron, right? Because one has positive charge and the other has negative charge so, when you mash them together those charges cancel out and you get a neutrally charged particle and also you get a neutrino. But, it's not that an electron and a proton are the constituent parts of a neutron. Neutrons are their own thing, it's just that statistically speaking all of the component parts of a neutron can exchange themselves, turn themselves into a new configuration of matter. And that new configuration of matter will be a proton and an electron. So, you can make a neutron by, essentially shooting a proton and an electron together if you shoot them together with enough energy. The idea here is that there are certain conservation laws that are conserved in any of these processes but beyond then, what the energy turns into is a matter of statistics. So, the deal is that with a certain amount of energy you can have one electron moving at a certain speed, one proton moving at a certain speed and one neutrino which is another type of particle moving at a certain speed.

[21:46]

Or you can have, take that same amount of energy, that same amount of electric charge and exchange them in for a neutron. And so the idea is that neutrons can turn into this combination of other particles. But it's not that the neutron is made of this combination of other particles. It's just that this collection of particles can randomly change into if you smash them together, a neutron and a neutron can randomly change back into this collection of particles.

Sarah: Okay. That's a fantastic explanation and I love it. And I was more talking about just my enjoyment as, you were saying earlier, the way that physics tends to take words and turn them into a physics thing.

Ben: Yeah, that's right. So, what I'm trying to contrast here is just how close to the word decay, in the natural sense, which usually means, breaks down into some component parts, particle decay is. But in this case particles aren't composed of the particles that they break down into. It's kind of a statistical process. If the energy density in one place is high enough and you can make, I don't know, it's kind of like changing a $5 bill into a bunch of coins and other dollar bills, a $2 bill and five loonies or, let's see a toonie...

Sarah: Wait, what particles do they have in Canada?

Ben: They have ah, loonies...

Sarah: No, not what coinage but what particles because if I was going to go across the Canadian border with some neutrons I assume that they would transition into something completely different.

Ben: The exchange rate these days, in neutrons, is about parity, so...

Ryan: Go on.

Ben: Okay, so, the moral of the story is, back to muons. Muons decay. Eventually they stop being muons. The deal is, muons are point like. They have no constituent parts. They're just there at a point. So, when they decay, it's not that they fall apart. It's that all of the sudden that muon just randomly rolls the dice and exchanges all of its energy into other smaller particles with less mass energy. So, neutrinos, and electrons, and then those guys all tear off in different directions. And so, because they're not all in the same place anymore they can't change back into a muon.

Sarah: Now, I do want to take a moment to appreciate the fact that you said muons eventually change, when we're talking about two microseconds.

Ben: Oh, yeah, that's forever.

Sarah: I don't feel like the word eventually applies.

Ben: So, there's an interesting thing here about muons turning into electrons which is that in particle physics, you know how I said that there like there are some conservation laws, like conservation of electric charge or conservation of total energy that, um, determine what things can turn into other things?

Sara: Yeah.

Ben: The idea here is that we have experimentally discovered a type of conservation law. It says that there is, essentially, this type of charge. It's not like an electric charge, but it's conserved like an electric charge, called lepton number or flavor that says, essentially, that if you have a box and there's one electron in it then that box has one unit of electron flavor floating around somewhere in there. And that electron flavor can exist in a few different forms. It can be one electron worth of electron flavor or it can be one neutrino worth of electron flavor. The electron has, kind of, two different siblings. There's the muon which we're talking about today and one that's much heavier than both of them called the tau or the tauon.

Sarah: Okay, so, enough of the Greek alphabet physics.

Ben: Oh man, let me tell you, particle physics is crazy about the Greek alphabet There's things called pions, and things called epsilons,

Sarah: Oh god.

Ben: Psions. Psion's a good one.

Sarah: There are other alphabets, there's more of them

Ben: Than Greek? Don't you like Greek?

Sara: I mean, I'm fine with Greek but like try something else every now and again. There's so many other alphabets.

Dianna: It's better, Greek letters I think, than like, colors or whatever and then calling them charm and...

Laughter.

Ben: Truth and beauty.

Dianna: Truth and beauty.

Laughter.

Ben: So, there are three different flavors, ah, muon, tauon, and ah, electron. And the deal is that any type of interaction that happens, you need to conserve the quantity of the electroness or muoness. And what that means is if you're going to turn a muon into an electron you need to take into account the fact that the flavors don't match. So, what you need to do is you need to add two more particles to the mix. For a muon to turn into something it needs another particle to carry away its muoness. So...

[26:47]

So it looses a mu-neutrino and then if the things going to turn into an electron, if you're going to make an electron you need something to carry away the hole that that electroness left behind and so you need an anti-electron neutrino.

Sarah: You need a rebound particle.

Ben: Yeah. You need kind of a, it's kind of a shadow particle. It shows up to cover the fact that your has no electroness.

Sarah: I mean, we've all been there right? You just loose your electroness and then you just need some particle to, like, fill that gap for a short time until you feel like yourself again.

Ben: Ah, when the muon decays it turns into one muon neutrino so that's where it's muoness went and then an electron and an anti-electron neutrino, because their total electroness is zero. There's an electron that's +1 and an anti-electron charge -1, a total of 0. The moral of the story is if your muon's going to decay, it's going to decay into three particles and that's super weird but you end up with a ton of neutrinos. Hey, lepton charge everybody. Isn't it crazy?

Dianna: Yeaaaahhhh.

Ryan: Well, actually, you have to conserve lepton flavor and the total number of leptons. So, there's three things that are conserved. There's electric charge because you have the muon changes into an electron and the two neutrinos have no charge. So, there you have conserved the negative charge. You've conserved the electroness and the muoness, right? So, first you have one muoness and you have an electron and an anti-electron neutrino. So, that's no electroness. And you have a muon neutrino which one muoness. And finally you also have to conserve the total number of leptons. So, you have one electron, that's one plus one muon neutrino, that's two, minus one anti-neutrino.

Ben: There's two infalling leptons?

Ryan: Yeah. But then the weird thing, we already know that the lepton flavor, the muoness and electroness is not conserved because we've observed the neutrinos can change from one type to the other.

Ben: Yeah.

Ryan: Electron flavor neutrino can just change into a muon flavor neutrino. And back and forth and back and forth.

Ben: Okay. So, Sarah. Are you particularly satisfied with muons? Do you feel like you know what they are?

Sarah: I'm going to say, I know what they are as much as I know what anything is and who among us can say that we truly know anything at all.

Dianna: I love that answer. It's amazing.

Ben: It's true.

Dianna: Like muons are really random particles that most people have never heard of but like there are some really cool applications of muons. So, they're not just useless particles.

Sarah: Okay, so what are some of the applications.

Ben: Aw yeah. Let's talk about cosmic rays. Let's talk about the interesting thing. Radiation from space.

Sarah: As in, outer space?

Ben: Yeah, yeah. So, This was actually the first place that muons were detected, um, and people have been trying to measure it for awhile. Do you remember when the LHC, the Large Hadron Collider got turned on and everybody was obsessed about black holes being created? And by everyone I mean crazy people in the media. Does that ring a bell? People were like, oh no, it's going to make a black hole and kill us all. Do you remember that?

Sarah: Of course!

Ben: Okay, so, physicists when they addressed this problem, literally said the physicistsiest thing of all, which is, I don't know, maybe. But they didn't seem particularly concerned about it as a possibility. And the reason we weren't worried about accidentally creating a black hole that would kill us all is because as strong as the large hadron collider is, it is nowhere near as energetic as various particles hitting the Earth's atmosphere from space. It's called cosmic rays. This is a phenomena where it's a weird, even distribution, it happens all over the Earth. Nobody's quite sure about where it comes from but they're like, they're little nucleus of atoms and they are moving super, super, super fast and when they hit the Earth's atmosphere, you know, as soon as they hit an air atom, that collision is so energetic that it has the capacity to generate any particle. It's more energetic than any Earth-based particle accelerator. So, the reason physicists were't particularly worried about a black hole is because, literally, this type of particle collision has been happening in our atmosphere since the dawn of time and it has not killed us yet. So, there's nothing we could do at CERN which would pose any risk at all.

Sarah: When you say that there's nothing you could do at CERN, is there nothing we could do, period, including various political events, that would cause a black hole that would destroy the Earth?

Laughter.

Sarah: Like even if we deserved it, a lot.

Ben: Oh, we do deserve it, but it hasn't happened yet, so...

[31:41]

Ryan: So, that is one of the big questions, is ah, what is making these cosmic rays, these super, super, super, super highly energetic particles that are coming from somewhere in the universe. We have some ideas, maybe exploding stars or big black holes accelerating gasses and things like that. But we really don't know. And these super, super, super high energy atoms when they hit our atmosphere they basically have zero chance of making it to the surface of the earth. Instead, what they do is they make these big collisions and ultimately one of the particles that comes out the most is the muon. In fact, the muon, because it has such a long lifetime of the whole two microseconds, is one of the only particles that makes it down to the Earth's surface. All the other particles that are created, and there's many, they have way shorter half-lives. They decay way faster than the muons and so they stay up in the atmosphere. So, we try to understand the cosmic rays that are coming into the atmosphere in several ways and the easiest way is to try to study the muons that come out of that and try to understand the size of the shower that you get, and things like that. And so the first muons that we discovered were these cosmic ray muons. We also know how to make muons in the lab but the first ones that we discovered because they are so readily accessible are the muons that come from cosmic rays hitting the atmosphere. To give you an idea, you get one muon per minute pure square inch centimeter. So, that's how many are coming down, right now, through the roof of your house, bombarding you.

Sarah: That's what that, I was kind of wondering...

Ryan: So, when you feel that tingle sometimes, it's just the muon passing through.

Sarah: Well, it's probably, like a thousand muons coming through, right?

Ryan: Well, one per square centimeter per minute.

Sarah: Wait, why is it per square centimeter instead of per cubic centimeter?

Ryan: Ah, the reason we use square centimeter instead of cubic centimeter is because we kind of picture it as, ah, here's a surface, how many are going through the surface? So then the unit of surface are square centimeters. So, it's kind of like, you hold up a tennis racquet and you count how many are going through the tennis racket.

Sarah: Yeah.

Ryan: So, there are a variety of experiments to look for these muons and other stuff that come from the cosmic rays. Ah, one that's pretty cool is in Argentina, it's called the Pierre Auger observatory. They have, essentially, a bunch of bathtubs scattered around the desert. Each one of these bathtubs has water in it and then they have very sensitive cameras looking at the water. The water is in a little tank so it's shielded so, I mean, there's no light. So, what they do is they have all these tanks and they wait for muons to go through the water. When a muon goes through the water it makes a very faint amount of light that the cameras pick up. So they scatter thousands of these bathtubs across the desert in Argentina and then they look every time that there's light in several bathtubs. They infer that those blips of light in multiple bathtubs all at happen at the same time, those must all come from a shower of muons from a cosmic ray that hit the atmosphere. The array of bathtubs covers many square kilometers, square miles in the U.S. and you can count how many bathtubs went off and that gives you an idea of how much energy the original cosmic ray had because the more energy the cosmic ray had the more muons it produces when it hits the atmosphere and the more bathtubs you'll see light up.

Sarah: Neat!

Ben: The picture here is that we're getting, is one particle hits the upper atmosphere and it hits it and it generates a whole bunch of weird other particles that are really short lived like fireworks. And then each of those has so much energy that when they hit something else or maybe they decay on their own, they'll turn into a small shower of other particles and so you get this cascade. Literally, like those fireworks that, where they blow up and then their tips blow up, that's literally what's happening only it's coming down towards us. And so, what starts out as a single particle turns into a whole shower of muons all moving in the same direction. And so, what we're doing is we're not just detecting a single muon, or a couple, we detect a whole glob of them moving past us and we say ah, that big glob, that is caused by a single cosmic ray and we can calculate how much energy the cosmic ray had based on adding up all of the energy from all these different muons.

Ryan: Exactly. So, I just looked up the size of this array, it's 50 miles by 50 miles and the bathtubs are like a mile apart.

Sarah: Wow. One bathtub per square mile.

Ryan: Yeah, something like that, yeah.

Dianna: Can I just, like, mention relativity real fast? So, Sarah, I just want to tell you that the first time I heard about muons was actually in high school and I really didn't care about them as muons yet. But I was taking a class in relativity which a lot of people don't take in their lifetimes. So, I was really lucky that I had a teacher that was super into physics and taught us all these conceptions about relativity and some of the crazy things like time moves at a different rate when you're going really fast.

[36:42]

And the length of things gets shorter when you're going really fast and crazy things like that. So, the reason why I at first learned about muons and why my teacher brought them up is that muons are supposed to decay in this two microseconds that we've talked about over and over. Um, which means that they should not be able to make it from the top of that atmosphere down to Earth where we detect them. They should decay before that. They're not going fast enough to make it down in that amount of time. They should decay into something else but they don't. We do detect them, we do see a bunch of muons which would indicate that maybe they are living longer but we know how long they live so what's going on? And what we ended up realizing was that this is an indicator that time moves differently for things that are moving really fast. So, time stretches out such that the muons can make it from the top of the atmosphere to the bottom. And it seems like it's a longer amount of time for us but it's moving slower for the muons and so I was learning about muons in the context of relativity. This weird fact that time changes speed when you're moving and these muons are moving very quickly so their time goes at a different rate and they're able to make it down.

Ben: So, this muon thing is totally crazy because cosmic rays, among their mysteries, is that they hit everywhere on Earth with pretty close regularity. There's some issues there with magnetic fields. Ah, they hit some parts of the Earth more than others but it's a pretty reliable rain. Insofar as they tried to figure out once upon a time where they were all coming from. They said, hey are all these particles coming from Jupiter and then so they would look at the data to see where all these different all over the world particles are coming from, are they all pointing towards Jupiter. No, they were just pointed in random directions of the sky. There's no rhyme or reason to how or why or when they fall. But the result is that they are actually pretty reliable. Oh, Dianna, tell us about tomography.

Dianna: Nothing would make me happier. So, muons can pass through things and eventually, you know, hit some things but they go through, obviously they go through a lot of our atmosphere and are not scattered as much as some types of light like x-rays. So, what we can do with muons is look into things that we can't otherwise look into. For example, some of the most interesting examples to me are looking into the pyramids. So we can, like, look through the walls of the pyramids and see what's inside.

Sarah: What?! No you can't.

Ben: Oh, you can.

Dianna: Oh, yes you can. This has been done. Yeah, so, it's kind of like an x-ray, right. Like, you send an x-ray through your body and some of it gets absorbed and some of it is scattered and you get this image on your detector on the other side. Like that's kind of the idea with muon tomography which is a word that I don't use very often.

Sarah: Tomography?

Dianna: Tomography, yeah. Like topography which is like the imaging of the surface of something, kind of. But instead you're mapping the inside, what physicists call like, the cross section, like slices of it. You can look inside and see, you know, like you see inside your body, you can see your bones inside. So physicists used muon tomography to image the destruction of the core of the Fukushima nuclear plant after it exploded. Because you kind of want to understand the damage that has been done and what the aftermath of that explosion looks like to be able to deal with dangerous nuclear material.

Sarah: Good job muons.

Dianna: Exactly! So, they use muons and they imaged the core, in, I believe this was in 2015, to try to understand where the core was, where the debris was, what it looked like inside and get a sense for how they were going to deal with the dangerous nuclear materials. You could also look in cargo ships, you can look for explosives, you can, you know, that's one of the coolest things about muon tomography. You can look into things and you can image inside, like, you don't have to actually go and cut something up. You can look inside. And in a better way in some senses than x-rays because they can travel farther into a material than x-rays and other types of radiation can.

Ben: Yeah, when they try to shoot electrons through things, for the most part they just kind of bounce off because they are very, very, very light compared to say, the nucleus of things. But, muons, they are so much heavier than electrons, that when they try to pass through material they just kind of go through like a truck through a field of corn.

Sarah: So, gracefully and without being noticed.

[41:35]

Ben: Yeah. So it's great because the source for the muons in these cases is often cosmic rays. These cosmic rays are just raining down on us and we're saying hey, let's say I want to see inside that volcano. I don't know when it's going to erupt. I need to know where the lava inside of it is. You can set-up a muon detector on the bottom side of the volcano and you can aim it and try to specifically detect the muons that are kind of falling through the sky diagonally and if they pass through the volcano then some parts of the volcano with the rockier parts will absorb more muons than the parts with the lava or something. And you can interpret the signals you get on the other side and deduce from those. It's just like an x-ray. Just like Dianna said.

Ryan: I have a correction. It was actually in the 1960s, the first time that they used muon tomography for the, to look in the great pyramid of Giza. Because he was looking for hidden chambers. It was an unsuccessful experiment at that time.

Ben: What? It was unsuccessful?

Ryan: It was Luis Alvarez that did it and he was from the Bay area because I remember going to Luis Alvarez something, something.

Ben: The first experiment was when they were, they had a mine shaft and they wanted to know how much rock was above the mine shaft and so they set up a muon detector under it and said, well, we know, vaguely at what rate muons are hitting the Earth above us and they deduced information about the rocks above it. So, it's a valid way of testing and you can do all sorts of fun things with it.

Ryan: Well, they had the idea a long time ago which is pretty cool. Because, you think, in the 60s, it was a rather incomplete picture that they had.

Dianna: Yeah. I mean, to be able to do this, you have to know, like we were talking about how many muons are going through your body per minute. You have to know that pretty accurately in order to look at the other side and be like, this is how many muons passed so therefore this must be what is in between the atmosphere and my muon detector

Ryan: You have to take a lot of things into account right. So what you're really doing is you're looking at the muons that are coming at all different angles. So, if muons, they come from straight above, the distance between the top of the atmosphere and you is shorter than the muons that are skimming the Earth basically. So, you have to take into account, when you do that, that the muons would travel longer and also have more time to decay. So, you have to correct for that before we can even do the tomography. So, it's pretty cool that he thought of all that.

Dianna: Right, right.

Ryan: A while ago.

Dianna: Muons are awesome. They're amazing.

Sarah: Okay, for each of you, what is your favorite thing about muons if you had to choose one aspect of muons, what would be your favorite thing?

Dianna: My favorite thing is something we didn't even mention. Which is that you can switch out an electron and switch in a muon to make a different type of atom. So you take your atom...

Sarah: No way!

Dianna: ... Switch out. Well it doesn't last very long because like we said, the muons decay. But, you can do that and you can make a different type of atom which is pretty cool.

Sarah: Is there an example of how that would...

Dianna: I mean, it's not like, this is something you do in a lab, it's not like a cushball from China has muon atoms instead of... like, this is something you do in a lab in a controlled way and it doesn't last for very long. So, it's not that useful but it's still kinda cool that you do it.

Sarah: Well, it doesn't have to be useful but I'm just curios what you know, like, what would, say if you were going to change an electron in an atom of argon...

Dianna: I don't know that we've done it, I honestly don't know that we've done it for more than hydrogen and helium. Um, so what is different about it is just that the atom is heavier because, like we mentioned before, the muon is heavier than the electron so you switch out an electron for a muon, you get more mass in your atom. So, your atom would be heavier, it would be obviously more unstable.

Ben: Yeah, the electron orbitals change position right?

Ryan: Yeah, it would be smaller, right?

Ben: Yeah. The mass of the orbiting particle is much higher and it's got more inertia and so it will cuddle up a lot closer to the nucleus.

Sarah: Is there a special name for an atom, like, a hydrogen with a muon?

Ben: It's Muonium.

Sarah: Really?

Dianna: No, it isn't.

Ryan: No, it's not. Muonium is an atom, it's an anti-muon and an electron.

Ben: Oh wow, yeah.

Ryan: So they replace the proton with an anti-muon.

Ben: Wow. Okay. Ryan, what's your favorite thing about muons?

Ryan: Actually, I dislike muons because the experiments I work on are very complicated because we try to avoid muons. So, we do our experiments in a deep, underground mine so we go through a lot of effort to get away from these muons.

Sarah: Wait, are you a part of those experiments that are trying to isolate particles that are prime-particles, I think. And they have this very deep, underground, it's like, distilled water and they're trying to just find the one particle that can pass through...

[46:35]

Ryan: Yeah, that's exactly it. So, what we're looking for...

Sarah: That's you??

Ryan: Is dark matter, yeah.

Sarah: That's so cool!!!

Ryan: Yeah, it's pretty neat. I do experiments in deep underground mines and it's cool because...

Sarah: Oh my god.

Ryan: The mines are like super dirty, right? I mean, because they're mines. But then, a mile and a half underground we'll have, like, these ultra clean lab where you have like a clean room and a clean suit. I always think it's kind of like James Bond lair where this hidden super modern state in a super dirty mine. It's quite cool for sure.

Sarah: That is so metal.

Ben: Yeah, well, go to the Titanium Physicist website and look up dark matter, we've done several episodes on them. But we haven't on dark matter detection too much because we haven't detected anything yet.

Dianna: Waaaa waaaa.

Ben: Okay, my favorite thing about muons is muon tomography. There's this really crazy thing that they did at Super Kamiokande. Super Kamiokande is a neutrino experiment just like Ryan works on. Or, rather, Ryan is working on a dark matter experiment but, essentially, neutrino experiments involve the same thing. They are big tanks of water where they are looking for neutrinos coming in, bouncing off, some water, making a little bit of light. That's essentially, these detectors. So, there's one in the middle of a mine in the the middle of a mountain in Japan. And the idea was that this mountain would shield the detector from cosmic rays, muons. They still get stray muons in. An the deal is that they've been detecting muons all over the place. Muons are noise in this case because they're looking for neutrinos which have a much subtler signal. Anyway, this group took all of the muon data and used it to figure out the topography of the mountain above them. And so, they made a 3D map of what the mountain above them must look like based on these muon trails. It's great. Anyway, I think that's my favorite thing. It's bananas.

Dianna: That is so cool.

Sarah: All of those things are awesome.

Ben: Okay everybody, that was absolutely fantastic. We learned so much about muons. Thank you Ryan, thank you Diana, you have pleased me, your efforts have born fruit and that fruit is sweet, here's some fruit. Ryan, you get a grape.

Ryan: Oh, sorry, I choked on the grape.

Ben: Dianna, you get a plum.

Dianna: Nom, nom, nom.

Ben: Alright, I'd like to thank...

Sarah: I appreciate that you want people to make eating sounds on your podcast and eating sounds are notoriously the grossest sounds.

Ben: I'm very stupid. Alright, I'd like to thank my guest, Sarah Gailey. Author of *River of Teeth*, her first novella. It's available now on Amazon for pre-order. Ah, thank you Sarah.

Sarah: Thank you, this was so much fun. You guys are great!

[49:14]

Ben: Hello everybody! So, it's time to wrap up the episode. This episode was pretty fun and boy was it a lot of work to edit it. But I'm pretty happy about how it came out. So, announcement time. First off, please give us an iTunes review. Or, tell other people about us online. Why?

Because people keep their love of physics hidden deep down in their hearts so if you tell them that you like physics, that there is a show you like to listen to, maybe they'll give us a listen. Alright, so, the best way for them to find out about our show is randomly tripping over us on iTunes and the best way to climb to the top of the iTunes Charts is to get iTunes reviews. Another fun announcement is that for the month of January we'll be selling our t-shirts on the t-spring website. You can find a link to it off the main page of our website. Just go to the right and click store. Ah, we're going to be re-releasing all the different classic Titanium Physicists T-shirt designs so, if you'd like one, the sale will close at the end of January and then t-spring does this thing where they need to sell a minimum number to print any of them. So, anyway, we're going to sell them super cheap just for fun. Okay.

On another note, we're still humbly soliciting your donations. Your donations go to paying our server fees and our project to transcribe all the episodes to buy our physicists new, better sounding microphones. Thanks to your support we've already transcribed our entire back catalog and so the money you give us will go to our improved audio quality project.

You can send us one time donations through PayPal off of our website or you can go to our sweet Patreon site and give us a recurring $2 donation. Speaking of which, this particular episode of the Titanium Physicists has been sponsored by a collection of generous people. I'd like to thank the generosity of
Carl Nagel, Adam Rabung, Louise Pantanella for their donations. I'd also like to thank Alex, W.T.L, Mr. Per Proden, Andrew Waddington, Mr. Jordan Young and John Lias. A Brittany Crooks, James Crawford, Mr. Mark Simon, Two Songs Gang of One, Mr. Lawrence Lee, Sixton Linason, Mr. Simon, Keegan Ead, Adrian Shonig, Andreas from Knoxville, Cadby, Joe Campbell, Alexandra Zany is great, Weena Brett, Eric Duch, Atein Raymond, and a gentleman named Peter Fan, 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, Insanity Orbitz, Robert Johnson, Madam 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 Kay, Thomas Shiray, a Mr. Jacob S, a gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, a Mr. James Clausen, a Mr. Devon North, a gentleman named Scott, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, and a Mr. Robert Stietka. So, that's it for Ti-Physicists 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. Also, on this particular episode of the Titanium Physicists Podcast my friend Tim Dobbs came to our rescue when the raw audio sounded, literally, like broken glass. Thank you Tim Dobbs for audio engineering the heck out of this episode. Tim has his own podcast called *Encyclopedia Brunch* where facts and trivia are discussed every week and it's one of my favorites. 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.

[54:09]

Ben: Ah, Sarah, do you have any questions before we really get rolling?

Sarah: Um, I think my only question is is it okay if I laugh every time you say muon.

Ben: Yes. You can.

Dianna: I'm curious, what is it about muon that makes you laugh?

Sarah: First of all, I was expecting from only ever having seen it written that it was going to be pronounced moo-on and I had a lot of cow jokes at the ready that I'm not going to get to use.

Laughter.

Dianna: Ah, that is so sad.

Sarah: I know. It's a deep disappointment that I'm going to carry to my grave.

Ben: Are you utterly disappointed? Seems like a lot of bull to me.

Sarah: Okay. Alright. Get out of here.

Dianna: I do, I do like the interpretation moo-on, for the pronunciation of this word. It is a muon. Have you... Ah, the first part is mew like the Greek letter (μ).

Sarah: Right, right right.

Dianna: So...

Sarah: ...know about Greek letters...

Dianna: This is one thing physicists do a lot is they name things with Greek letters so muon is no exception

Ben: Um, Okay. Moral of the story. They're little particles, they look like electrons, they're super heavy. They, eventually, break...

Sarah: They're not technically dense

Ben: They're not technically dense . They decay.

Sarah: Oh. Brilliant.

Ben: And they decay into electrons and some other junk.

Sarah: And they don't decay in a way that I think is clever to refer to them as decaying. They decay in that other way.

Ben: Yeah. Because they're not made of stuff. They just spontaneously turn into other stuff. Like how a zombie can spontaneously turn into two frogs and a vampire. That's way better.

Dianna: I have a question, Sarah, for you.

Sarah: ...frogs... how dare you say that a zombie could decay into a vampire. I'm embarrassed for you.

Ben: Does, do I have that backwards? Do vampires decay into zombies? That makes more sense.

Sarah: I can't even begin to explain...

Ben: Maybe a vampire decals into...

Sarah: That would be a whole other podcast.

Ben: A vampire decays into a zombie and an ugly dog.

Dianna: You can't even begin to explain? Does that mean we broke the writer?

Ben: Yeah, I guess so.

Sarah: Ha, it doesn't take a lot to break a writer.

Dianna: Yes! I have a question for you Sarah. When was the first time that you heard of muons?

Sarah: When a gentleman, I'll never forget it, it was this amazing moment in my scientific education. A gentleman by the name of Benjamin Tippet sent me a message on a website that you may remember. It's called Twitter, you know, it might be from too long ago but he sent it to me and he said, hey, do you want to come on this podcast that I'm doing. And a podcast is like a radio show but for the internet. And he said we're going to talk about muons. And that was the first time that I ever heard of them. I'll never forget the day. It feels like it was just yesterday.

Dianna: It feels like it was just two microseconds ago.

Laughter

Sarah: Not that long ago.

Dianna: Nothing so long in your life. Okay, so, like, I'm curious though, having discovered recently in your life that there's this whole world, a zoo, as they like to say, of particles. Is your mind blown.

Sarah: Yes is the satisfying answer.

Ben: I know, right.

Sarah: I mean, I've been aware of and uneducated in particle physics for a long time and my husband is actually a physics teacher at the high school level so I tend to do a lot of listening to explanations of physics concepts that have included, you know, brief references to particle physics that I have listened to very attentively as I do with everything that my husband explains to me and I'm saying that on the record.

Laughter.

Ben: I will not delete you saying that.

Sarah: It is always exciting to learn about new aspects of the field especially if there is the possibility that he doesn't yet know about them and I can go and sound super smart to him.

Dianna: Yes, always. I'm excited to get to be talking about...

Sarah: What is something about muons that you hate having to try to explain?

Ben: Lepton conservation. No, lepton number conservation. (Funny gross sound) Did you hear that? Gross.

Laughter.

Sarah: The disgust in your voice.

Ben: I don't know why I signed myself up to do that explanation. I'm like, yuuuuuuukkkkggg, I don't know. There are these numbers, they're abstract, ah, somehow they get conserved. Ryan, what do you hate about muons?

Ryan: Ah, I don't think that one was by the...

Ben: Dianna, what you got?

Dianna: I don't like having to explain why we call things what we call them.

Laughter.

Dianna: Like, there are so many words in physics that are ridiculous.

Ben: Yep. We did a show once on pasta matter.

Dianna: Oh gosh.

Ben: Ah, the matter inside neutron stars, ah, is named after different kinds of pasta. So there's spaghetti matter...

Dianna: Do you mean pasta?

Ben: Yeah. Yeah.

Ryan: Oh, yeah, Americans don't say it, they say pasta.

Ben: Oh, oh, oh, I see.

Dianna: I was like, pa, pasta? What?

Sarah: Benjamin, are you Canadian.

Ben: Yes.

Sarah: Uuuugh. I finally did it, my Henry Higgins moment.

Ben: It was a very, it was a good deduction. I'm very impressed.

Sarah: Zero work. You said sorry, like, an hour in a half ago.

Ben: Sorry.

Laughter.

Sarah: Ah, what do you call the macaroni and cheese that comes in a blue box?

Ben: Ah, that's Kraft Dinner. You want, that's Kraft Dinner you're talking about.

Sarah: It's Kraft Dinner, American friends...

Ben: Yes.

Sarah: It's Kraft dinner. That's the world he lives in.