Episode 51: Tabled Tops with Noah Zimmerman

Physicists: Ben Tippett, Abby Shockley, Fiona Burnell

The Titanium Physicists Podcast

www.titaniumphysics.com

Transcribed By William Blewitt

Ben: Hi everyone. This episode is good and there's lots of good news. So listen closely to the end of this episode for some good news. There's a bunch of things, but I wanted to get this announcement out of the way: I'm going to leave my Fortress of Solitude to make a rare public appearance. I'll be attending the Nerd Nite Block Party in San Francisco this Friday, October 24th. It's a big party to kick off the Bay Area Science Festival in San Francisco and I'll be doing a recording of *Science…sort of* with Ryan Haupt and Kelly Weinersmith. The recording is going to happen at 6PM at the Piston & Chain. More info will be available on the website. I hope to see you there.

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 50 episodes now my team and I have brought you to the very frontier of knowledge of physics and astronomy. And still our mission goes on, to present you with your birth right, an understanding of the universe. I've travelled 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 Physicists. You're listening to the Titanium Physicists' podcast, and I'm Ben Tippett, and now allay physic!

[02:24 minutes]

Ben: Hi everyone, I want you to think about Star Trek for a second. Ask yourself, of all the technologies in the science fiction universe which one of them is most audacious? I'll give you a second...Okay, now let's all say the answer out loud at the same time at the count of 3: 1...2...3...Scanners! What's that? You didn't say scanners? Well you're wrong. I mean haven't you ever asked yourself how is it that people up in space can somehow scan an entire planet and know about everything on it in minutes. I mean do they have an all-seeing Odin All-father trapped inside a box or something. I mean maybe if they had a telescope they could look down and see all the visible things that are visible or shining or reflecting light. But how can they see stuff that's inside houses. Something penetrating maybe like x-rays or neutrinos, but in that case wouldn't all the walls and roofs of the houses be louder or give a louder signal than whatever's inside it. And where would this penetrating radiation come from? Uh, does the Enterprise launch a satellite onto the other side of the world and irradiate everyone on the planet with x-rays? Anyway, it just doesn't make sense. How can you perceive something which is tiny and also surrounded by other stuff? There is in fact a technique. It was invented in the mid-twentieth century which does just that. I mean it doesn't happen in space. You need a big monster magnet to do it, but it's called magnetic resonance. And it uses the differing magnetic properties of atoms and materials to scan and detect the subtlest constituents of a sample of matter. And today on the Titanium Physicists podcast we're going to be talking about nuclear magnetic resonance or NMR as the pros call it. And today on the Titanium Physicists podcast I'm pleased to welcome Mr. Noah Zimmerman. Noah is a mechanic by trade and he has long been an admirer of science and skeptical inquiry. He's totally fascinating and today he's agreed to be a guest on one of our most ambitious topics to date! Hi Noah.

Noah: Hi Ben. How are you?

Ben: I'm excited! So for you today I have assembled two *fantastic* Titanium Physicists. Arise Fiona Burnell!

Fiona: Boink!

Ben: Dr. Fiona did her undergraduate degree at UBC and her PhD at Princeton. She's now faculty in the physics department at the University of Minnesota, where she's a specialist in condensed matter. Now arise Abby Shockley!

Abby: Oooh!

Ben: Dr. Abby did her PhD at the University of California Davis. She's now at the University of Paris-Sud XI, working at the Laboratoire de Physique des Solides as postdoc studying nuclear magnetic resonance.

[04:55]

Ben: Alright everybody let's talk about looking into stuff without poking it with a stick. So Noah, have you ever heard of nuclear magnetic resonance before?

Noah: I have never heard of this and I'm kind of surprised because I consider myself a science aficionado.

Abby: So you probably have just by a different name, "Magnetic Resonance Imaging".

Noah: Oh MRI.

Abby: Yep, that's nuclear magnetic resonance.

Noah: Oh I see. Okay.

Ben: Apparently they dropped the nuclear from the title because it scared Americans. Yeah so it's interesting, depending on where you go, sometimes they call it MRI and sometimes they call in NMRI. I thought they were different at first. I mean I'm not a nuclear magnetic resonance imaging physicist so I thought, “Oh wow, they've got magnetic resonance down to a nuclear level have they?” But I guess it's always been NMR or NMRI; they just dropped the 'N' in some places. Let me give you a picture of how this works. Someone will bring in a little vile or something, a tiny little sample and say, "Okay what is this?" Maybe it's like an organic molecule dissolved in some water or alcohol or something, or a little semiconductor something. And they'll say, "Hey what is this? Let's study how this thing works." So what they do is they put it inside a *great big magnet*. So you've seen the NMR machines right? They have those big donut-shaped machines that they put people inside?

Noah: Yeah.

Ben: That's a magnet! That's a huge monstrous electromagnet.

Noah: That's all it is?

Ben: Yeah…and electronic components. I mean most of that is to make a big magnetic field. And so what they do is put you inside a magnetic field, and then they hit you with essentially what are radio waves, give or take. And then based on how the atoms in your body respond to it, inside this big magnetic field, they can tell what makes you up, or what's inside this little vile.

Noah: Fascinating.

[06:49]

Ben: Yeah. So there's one principle underlying all this stuff that you need to be familiar with before we even get too deep. Have you ever heard of precession?

Noah: No, I haven't.

Ben: It's not procession, like a march. Precession - it is in essence what happens when you try to tilt a spinning object. There are two fundamental features to describing precession that goes on here. The first one is you need something that is spinning. The second is that you need to apply a force along its axis to a tilt in it. We'll get into some examples so that you can imagine it a little bit better. I want you to imagine – do you ride a motorcycle by any chance?

Noah: I do.

Ben: Okay, how do you turn a motorcycle?

Noah: You sort of lean and push the handlebar down a little bit in the direction you want to go.

Ben: So let's say you're on the highway going 300mph. Can you use the handlebars to turn?

Noah: Not really. It’s dangerous at that speed.

Ben: No, you have to lean, right?

Noah: Right.

Ben: So the deal is that your leaning causes the front tire of your bike to turn.

Noah: Right.

Ben: …in the direction that you want to go. So if you want to go left you lean left and the front tire will swivel left and that will cause your bike to turn left.

Noah: Right.

Ben: And in effect it's you turning the handlebars but you’re doing it by leaning instead of pushing on the handle bars.

Noah: Indirectly, yeah.

Ben: Indirectly yeah. That effect is precession. That's essentially what we're talking about. The deal is if you take a spinning object, imagine you’ve got a bicycle tire, or some wheel in front of you spinning, on either side of the axel there’s a little handlebar. If I push my right arm forward and pull my left arm back, the way you would if you were trying to turn the wheel, what happens is the wheel will try to tilt diagonally so your right hand is above your left hand, and the axis becomes diagonal. In essence it's what happens in your motorbike when you try to turn.

Noah: Right.

Ben: Before we start talking about nuclear magnetic resonance there are all sorts of systems that precess naturally. All you need is, like I said, a force, so something that is trying to twist the axel that the object is spinning on. If you try to twist the axel you'll see that the object tries to push itself in a direction perpendicular to the direction that you're twisting. So if I lean to the left the front tire will swivel. So there's all sorts of occasions in the natural world where this happens. One that I like the most is that the Earth is spinning right?

Noah: Right.

Ben: So it has an axis of rotation, just like an axel, going from the North Pole to the South Pole, so it's spinning around this line. But it's tilted, right? That's why we have seasons, because the Earth is tilted. It's not perpendicular with the Sun as it goes around. It's kind of swiveled sideways. And so the deal is is that as it spins around the Sun, the gravity of the sun is trying to twist the axis that it's spinning on just a little bit. And so the Earth is precessing in position as it goes around the Sun. And so the net effect here is that the North Pole, this axis that the Earth is spinning on, the North Pole, it changes direction really really slowly. So right now the North Pole of the Earth is pointed towards the North Star. But over time it won't be. Over time it will be pointing into deep space or towards some other star. And the axis that it's rotating around will essentially move in a circle. I'm not sure if that's the best visual, I just like that piece of trivia. In fact, back in the Egyptian days it wasn't pointing at the North Star right? I think the time scale of precession is...(26,000 years).

[10:07]

Ben: Another example, is like a top, like a kid's top. Noah, when was the last time you played with a top?

Noah: I'm trying to think...that would probably be Hanukkah, many years ago.

Abby: Yeah dreidels.

Ben: Yeah. I mean, usually when you try to spin a top you try to spin it so its axis is pointed up right? But you never manage to do it because hands are clumsy things. So instead, what will happen is that you'll spin it and its axis will be pointed slightly off, tilted right? But it doesn't fall over when that happens. Instead as it spins it kind of wobbles around in a circle. So the axis itself ends up rotating in a circle. And you see the tip of the dreidel in this case moving in a circle.

Noah: I know exactly what you're talking about.

Ben: Perfect! That's precession! And so in this case the rotating dreidel is spinning, but there's an external gravitational field that's trying to twist the stem of the dreidel down towards the table, which causes it to move in a circle.

Fiona: The thing that is sort of unusual about tops and bicycle wheels is that once you spin your top it wants to stay standing up. And this is something that I think a lot of us have experienced personally is once you get you're bicycle moving it's not at all difficult to keep upright. But of course if you try to stay on your bike and the wheels aren't moving it's actually pretty difficult. And when I was a child I didn't understand about angular momentum and I basically spent an entire afternoon in the backyard with my bicycle trying to be able to just stand upright on this bike. And my mother eventually came out and said "What are you doing?" And I said, "Well I have to learn how to do it while I’m standing still first before I can try it while I’m moving", which I assumed would be more difficult. Yeah, so I think that kind of illustrates what is sort of counterintuitive about this, that when something is spinning it wants to stay aligned in the same direction and if you try to change that direction, like if you go to lean over on your bike, you start falling over. Effectively you feel a force that's kind of pushing you back up. So instead of just flopping over as you would on the stationary bicycle, you more or less stay upright and you use that force to turn. And that's kind of central to why once you spin your bicycle wheel it will precess or why once you spin your top and try to push it over a little bit it will precess rather than just falling on the table as it would if it were not spinning.

Ben: Yeah that's how that trick works when you're teaching a kid how to ride a bike; you hold onto the back and you balance them until they're going fast enough and then you let go. And they can't tell that you're not holding them in place because…

Abby: Yeah but then they're always mad that you did that.

Ben: Well that's just the first of many betrayals they'll feel over the course of their lifetime.

[12:45]

Fiona: So Noah, do you like magnets?

Noah: I love magnets. But I don't know how they work.

Ben: (Laughs) Oh no, a juggalo!

Fiona: I don't know if we have too much time to talk about how magnets work. Let me try to give an analogy that is germane to what we're trying to understand. So Ben told you about precession. And to understand what happens when you actually do NMR or nuclear magnetic resonance, you have to understand what happens to little magnets. So a magnet, if you put it in a magnetic field, it turns out that magnets also precess. So let me come back to the top that we were talking about. So what happened was we took our top and spun it around. We know that when it’s spinning fast enough the top doesn't want to fall over. So there's effectively some kind of force that it feels that is preventing it from just toppling over. So now if you turn it sideways a little bit, so now it's tilted, and now it really wants to fall over, you basically have gravity sort of pulling it down. And what actually happens because it wants to stay standing up, it's going to start precessing. Did you ever do this thing when you were in elementary school where you get all those little iron filings and you put them on top of a desk and then you take a magnet and you put it underneath the desk and all the iron filings stand up?

Noah: Yeah I did.

Abby: Do you remember that toy with the guy with the mustache that you could draw with the magnetic pen and put his mustache on?

Ben: Oh yeah, yeah, right!

Noah: Yeah.

Fiona: What's happening to your iron filings basically, they're on the top of the table, and your iron filings can become little magnets. And when they become little magnets, and that happens quite easily, if you put them close to your big magnet, they essentially become little magnets. And they essentially, the reason your iron filings stand up is that they're little magnets and those little magnets want to align themselves with the magnetic field from the big magnet. So that's one of those cool things you can do is you can actually see them stand up because they feel this rather strong force telling them they want to line up with the magnetic field of the big magnet. That's the thing that's generally true. Anytime you have a magnet, no matter how big or small, and you put it close to another magnet, it wants to line up. They like to be pointed in the same direction. So basically what NMR is going to exploit is that inside all kinds of stuff, water, metals, pretty much everything that we encounter, you know it's all made of atoms and in these atoms there are little tiny magnets. And when you put those magnets in a big magnetic field, they're all going to want to line up with the field. And then if you manage to basically tilt them with respect to that field, then they're going to start to precess exactly like your top. And that's kind of the basic phenomenon which allows NMR to work.

Noah: So you're saying the atoms in my body are magnetic?

Abby: They're not magnetic like a magnet you would stick to the fridge…

Fiona: (laughs) You do not stick to the fridge.

Noah: Let me go try that right now.

Ben: You might stick to the fridge for other reasons.

Fiona: Like if you're covered in Velcro.

[15:50]

Ben: Or maybe you really like food. Taking a step back here, there's a connection between electricity and magnetism. Have you ever played with an electromagnet before? Surely, you're a mechanic. You've got the solenoids in the starter right?

Noah: Right, right.

Ben: Yeah, so it's just like a coil of wire, and then when a current of electricity passes through it, it picks up a magnetic field. The deal is that there is a connection between moving electric charges and a magnetic field. A short answer is that you can get a magnetic field that points up-down by spinning electric charges in a circle. Which is essentially how your electromagnet works. You've got a coil of wire and when you make a current of electrons circling the coil of wire and in doing so induces, it creates a magnetic field, pointing down through the middle of the circle. Alternatively, we were talking about a bike tire. So you know how if you take a rubber balloon and you rub your head against it, it picks up an electric charge?

Noah: Yeah and it makes your hair stand on end. Static electricity.

Ben: Yeah, yeah. So imagine you're maybe out in space or something and you rub your hair on a bicycle tire, so that it picks up an electric charge. So then all around the rubber rim of the tire is covered in little electrons. If you then spin the tire, you'll have electrons moving in a circle, and the result is a magnetic field that points up the axis, in the direction of the axis of the rotating tire.

Noah: Wow, okay.

Ben: So if I went out into space, and let's say I spun my bike tire covered in electric charges and it ended up producing its own little magnetic field, it wouldn't precess normally because there is nothing pushing on the axis of the frame. But if I then put that spinning tire inside a big magnetic field, so a magnetic field pointing, I don't know, up-down or something, then depending on the orientation of the tire, if the axis of orientation wasn't pointed in the direction of the magnetic field, then it would feel a force pulling it into the direction of the magnetic field. And we've already talked about what effect something spinning and a torque on it produces; it causes it to precess. So if you did this in space with your spinning bike tire and you put it in a big magnetic field that wasn't quite aligned with it, the force from the external magnetic field on your spinning tire would cause your bike tire to precess, just like the dreidel on the table. The axis would make a little circle. And that's essentially what's happening. You know, everything is made up of atoms. You've got protons and electrons. You know, protons are spinning a little bit. The overall nucleus of an atom will be full of positive charge that is… well quantum mechanically there's some devils in the details there, but mathematically it looks like it is spinning. So let's just say it's spinning (laughs). You've got these little protons of positive charge and they're spinning. So each nucleus has its own little magnetic field, just like your spinning tire.

Noah: Incredible.

Ben: Right, so if you put that in a great big magnetic field it will precess a little. So what happens is you start off with your little sample or whatever and you put it in the great big magnetic field, and then just like if you took a whole bunch of compasses and put them in the magnetic field, they all orient themselves in the direction of the magnetic field. Let's say the magnetic field, oh it's *huge*, these magnets that you put it in it's...

Abby: They're really really big. So if you think the Earth's magnetic field, this thing that makes your compass go, is something like a 100 Oersted; it's super small. So typically in the lab, a magnetic field that I might be measuring, I have a 7 Tesla magnet in our lab, and 7 Tesla is 70,000 Oersted. So in comparison to the Earth's magnetic field, your thousands of times stronger, than what you just feel from the Earth moving around.

Noah: Wow. In one lab?

Abby: Yeah, usually an NMR lab has multiple magnets that are that strength or higher.

Ben: That's why you're not supposed to bring any metal with you when you go to one of those NMRI sessions because it will get pulled into the machine!

Noah: I've heard stories about that, like an oxygen tank flying through the air like an unguided missile.

Fiona: Yeah you can find exciting videos of things being smashed using big magnets.

Abby: We have the biggest magnet in the world in the United States and it's in Florida. Its 45 Tesla. It's huge. So you go and stand on top of this platform and my PhD advisor liked to tell this story where he had metal rods down the middle of his shoes and I guess he just didn't realize it until he went to this magnet. And he would try to walk, but the field was so strong that it would turn his foot and so he couldn't really walk properly in the shoes that he was wearing.

Noah: So this magnet was so strong that it took the shank in his shoe and held him in place. It's incredible.

Ben: It rotated it like an iron filing, right? So he only could be walking in the direction of the magnetic field. He could only walk directly towards or away from the machine. He couldn't walk sideways (laughs).

[20:45]

Abby: Well so we were talking about all these nuclei are made up of different parts and they're all spinning like little magnets. So what you're doing when you have an NMRI measurement is...do you know how a radio works?

Noah: Yeah.

Abby: You're basically taking something that should pick up a radio signal, but you're using it to measure what's going on with these little magnets that are spinning around. Every nuclei has its own specific property that tells you what frequency it's at. So it's like how do you tune to your favorite radio station? The same thing with the nuclei; you want to tune to the channel that goes to whatever nuclei you want to measure. This is sort of an aside of something that used to happen in our lab, you know the nuclei tells you what frequency you have to measure at, and sometimes when we're taking these measurements we don't always see what we're trying to measure but we see backgrounds like FM radio signals as well. So we used to have a really big problem with this. So what they do is put aluminum foil all over your measurement. So you would have to come in and I would always know someone is having a bad day because there would be aluminum foil like strewn all over the lab and someone would be sitting on the floor with a huge roll of aluminum foil.

Noah: Would they wear an aluminum tinfoil hat?

Abby: Not usually, unless it was a particularly bad day. They always said it was kind of his crazy scientist art project. But so you have these set frequencies you're tuning to, and that's where your nuclei is going to be. So you put all your stuff in a field and you have a frequency. So it doesn’t work exactly like a radio. So instead of the frequency coming out all the time, your only putting on the frequency for set periods of time, and that’s going to tell you something. So you can in a sense control how the spins are moving. So with the analogy that we were using before of the bike wheels, it’s sort of like I’m on the outside turning to bike wheel or turning the magnetic spin by applying some sort of radio frequency voltage to whatever it is that I’m trying to measure. So I can control whether I’m staying upright or whether I’m making the spins turn.

Ben: Right so you take your sample and you put it inside this big magnetic field. And then all the material inside it, all the little nuclei are going to reorient themselves, just like Fiona’s iron filings. They’re all going to point in the direction of the magnetic field. And then you’re going to hit it with a secondary oscillating magnetic field, about radio frequency. That’s why you have to cover everything in metal, to keep from hearing the Fugees in your data. And doing so changes the direction of the magnetic field for all of the atoms wherever they are. It's like – imagine your bike tire in space; it's spinning inside a big-giant magnetic field, and you go over and you kick it. And so it started out oriented in the direction of the magnetic field but kicking it twists it so that now it's lying in a different direction relative to that original magnetic field. And now that it's tilted, now that the axis of rotation is different from the big external magnetic field, it's going to start precessing.

Fiona: You still have the big magnetic field on right?

Ben: Yeah.

Fiona: So you have like a whole table with like lots and lots of little tops on it, and all these tops are spinning. And then you turn a fan on or something like that for a little while. So you're actually tipping all of these tops. You're going to push them so they're all going to kind of tip a little bit with the wind. And then you turn the fan off. So now the tops are pointed a little bit away from straight up and down and that's when they start to precess. So you can try that at home if you had like a 100 friends who could help you spin them.

Ben: (laughs) Yeah a 100 friends, spin all these dreidels. And there it is the analog for NMR

Abby: So we can control how the spins move based on how strong the fan is or how long you apply the fan for. And so maybe usually you start with them all pointing up but you can play with how far you want to tilt them to see what kind of information that you're getting. So do you want to tilt them like 30 degrees or 40 degrees? Do you want to tilt them 90? And that's sort of the game that we're playing when we're trying to take an NMR measurement, is how much do you want to tilt them and in what order do you want to tilt them. Does that make sense?

[25:16]

Noah: It does, but I'm a little confused about the imaging part. How do you take this tilt with this oscillating radio wave and turn it into a picture on the screen?

Abby: So for MRI what they're imaging is when you tilt these little spinning tops eventually after you've tilted them and after you've turned off the fan, they're all going to try to come back to the position that they were at before you tilted them. And if that motion is a really specific time variable that is unique to the system and it's unique to whatever is going on in your body. So my friend is a med student so they had to go over what you have to do when you get an NMRI scan. And it's something like if you're going to have an MRI and you have to look for a cancerous tumor in your body, well the time scale for how quickly these spins are going to come back to the position that they started at is going to be different inside the tumor than it is in the normal tissue. So they can see by how these different sections are moving in these different places, whether or not there's something wrong with you.

Noah: Okay, that makes sense.

Abby: So that's sort of the game that we're playing. So there's two different time scales that you can talk about. The first is the inversion time scale which is how long does it takes for you to come back to your equilibrium position once you've been flipped. But then there's another one that is if you've been flipped something like 90 degrees spins also precess; they all have their own unique z time and they have a unique x and y time for their precession. So the typical analogy for that one is that it's like runners running a race. So when you start a race usually there are people who are super-fast and there are people who are super-slow. So this is like what the spins are doing. Some of the spins are moving really fast and some aren't moving very much at all. And you can get a measurement of how far dispersed these time differences are by controlling stuff about how you apply the times when you turn on your fans with your gyroscopes. Now I'm getting kind of confused between our classical analogs and the real systems.

Ben: Yeah. Okay, so Fiona was explaining these things in terms of tops on a table. They all start off spinning up and then you turn on your fan and that flips them over kind of sideways at an angle. And then when you turn off their fan, they're all going to behave differently.

Fiona: I think you might want to think about if some of your tops are spinning faster than others or some are bigger than others, maybe they're different shapes. So you can imagine that they're all going to precess. They're all going to feel this same resistance to falling over and that's going to make them spin around just because they're spinning.

Ben: Yeah, the rate of precession will depend on how heavy they are or how fast they're spinning. There's a bunch of different things that will determine how fast the top will go around in a circle. I mean it sounds like based on our explanation it's wonderful, but it's really noisy if you do it with atoms, because there's so many of them. There's gabillions of atoms and they're all kind of doing their own thing. Even if you did this thing with the magnetic fields, how would you get any useful information right? I mean it seems to me based on this explanation like it would be too noisy to even be able to tell anything useful. So the nifty thing about this is that we're talking about atomic nuclei, and the rules of quantum mechanics are in play here. So it's not as if for nuclei they can take on any rate of spin they want or a continuum of masses.

Abby: They're restricted to certain bounds that they're allowed to have.

Ben: Because of quantum mechanics they can only spin with one of two numbers. They can only spin in 1 or 2 or 3 direction. There's a finite number of discrete possibilities for the ways each atom can be. And so the result is, that when you take all your quantum mechanical tops and you spin them all, they're all kind of indistinguishable. They all have similar characteristics, or maybe there's only one or two different possible characteristics each top can have. And so the result is when you turn your fan on and you turn your fan off, there isn't a continuum of noisy behaviors. Some of them will precess and one rate and some will precess at another rate. There's a finite number of discrete possible rates that they can precess. The moral of the story is in Fiona's tabletop you spin all these dreidels and they're all spinning but there's only a certain number of different possible ways each one can spin. You turn on the fan and then you turn off the fan and each of them will start precessing and the rate at which they precess depends on these internal variables. But there's only a finite amount of rates that each one can precess due to quantum mechanics. So the story that I've been told by essentially Abby. It goes like this: they turn on Fiona's fan, all of the little dreidels tip sideways. You turn off the fan and they all start precessing. But then you hit them with another type of fan that causes them to switch the direction that they're precessing in. They go from precessing let's say clockwise to, after you hit them with the thing, precessing counterclockwise, until they move back to the original position. And the amount of time it took should be the same theoretically based on these pure quantum numbers. But here's the neat thing: So it's been compared to essentially a race. You have a class full of people; I guess there's 4 different types of people. You turn off your first fan and that's like telling everybody to run. Each of them starts running down the race track. Some of them run faster and farther than others, but then you fire a gun and they all just have to turn around and run back. They'll all end up crossing the starting line…

Abby: At about the same time.

Ben: Because you know one might have run farther than the other but he's also running faster. So he'll run out as fast as he runs back.

Noah: Great analogy.

Ben: I know! Here's the really neat thing about that: they should all arrive back at the same point if they're all kind of pure. But they're not pure; they're interacting with each other. So the spin of one atom will interact with the magnetic spin of another atom. So they're interacting with each other as they're precessing and moving. And this interaction with each other depends on the internal structure of the system. So if you're testing chemicals then one atom might be attached to another atom using two electrons, and then a third atom using one electron. And then that electron configuration will kind of determine how they interact with each other as they do it. And so it's kind of like you have a race between four people, and they should be all arriving back at the same time after you shoot your gun and stuff. But as they're kicking each other and holding each other back as they run, they're going to be arriving back at slightly different times. It's not going to be perfect. But that lack of perfection it tells you a whole bunch of information about the material. You're looking for these differences away from being the pure amount of time that you expect them to get back because that's an indication of what kind of internal structure there is. Essentially you're testing the characters of the racers, instead of testing how fast they can run

Fiona: It's a little bit like if you had a race and you took Olympic sprinters and they're focused on running. So they're all going to run out and they here the turn-around gun and they're going to turn around and are basically all going to get back at the same time even if some of them are faster than others. But if you then repeated this experiment with football players, of course the football players' first instinct is going to be to start tackling each other. And so even though in theory, you fire the gun and they should all get back at the same point, you're going to see a much larger variation because of their fundamentally different behavior, in terms of the way they interact with each other.

Ben: So what you do is you sort of scan around. You know what the theoretical should be and then you're looking at the differences between the theoretical-should-be peak and then how they're actually interacting. And that tells you a ton of about the chemical composition or the lattice structure…

Abby: Or the dynamics of the system. So it's like, do know the protein folding experiment? My neighbor is working on this now. There was this thing on the internet, like a few months ago, about all these people, like Weinmann, solved this problem that scientists couldn't really solve on this protein-folding thing because they had turned it into a game. So it's something my neighbor is now using to study how protein folding works.

[33:19]

Ben: So to review, every nucleus has a spin, and so every nucleus has its own magnetic field depending on what type of material it is. And then you put them all in a huge magnetic field, maybe made by an awesome superconductor or something. And then all the internal nucleuses line up with this external magnetic field. And then what you do is, you hit them with essentially another magnetic field that causes them all to tip over. And then once they tip over they'll start to precess. So we understand theoretically how they should be precessing and how they should be realigning themselves with the larger external magnetic field. And so we're looking at differences between what we theoretically expect and what they actually do to deduce information about the character of the material or the chemical composition or the atomic structure.

Noah: Like a scanner in Star Trek.

Ben: Like a scanner in Star Trek! Okay, would you like to hear about applications in magnetic resonance?

Noah: Yeah

Ben: Yeah me too. Hit it someone who knows something.

Abby: One of the biggest things that it's used for is MRIs. That is really nice because you see the same thing as you would with an x-ray. X-rays are kind of not good for you at all because they give your body a lot of irradiation and that can cause bad things as well. But an NMRI as a test, there's nothing harmful about being in it, unless you forgot to take something metal out of your pockets, or you have a pacemaker or something like that. An MRI is actually a very safe and fairly effective way to look at what's going on in someone's body without having to open them up or something like that. And that's pretty cool I think.

Fiona: The reason they didn't call it nuclear magnetic resonance is because when people hear the word 'nuclear', and especially at the time the technology was being developed, that really evoked nuclear reactions and radioactive waste and kind of stuff that sounded kind of scary. But really the word nuclear refers to the fact that it's just in the nucleus of the atom there are spins. And little tiny magnets. And those are typically the little tiny magnets that are being measured. So the great thing about the fact that this technology is very safe is that you can take a lot of pictures. You can take many many different scans, because unlike an x-ray you wouldn't want to take that many x-rays; that would potentially be harmful to the person. There's no reason you can't take a hundred different sort of slices. And so they use this to construct three-dimensional medical images. They also use it to do dynamical measurements in time. They now do cognitive psychology experiments: How the blood flows to different areas of the brain when people are doing different kinds of tasks. So that fact, although it sounds like a simple thing has really enabled the technology to be used for a lot of stuff.

Abby: Yeah, there's something called a functional MRI where psychologists do experiments where they give you different things and they look to see what parts of your brain you're using. This is going to be another weird one but at the place that they have the big magnets in Florida, they have a magnet that is big enough that they put live mice in it and they induce a migraine in the mouse and then they took a medical image of it to see what was going on after they gave the mouse a migraine. And they found out you actually get a build-up of Sodium behind your eyes. So sometimes when you have a migraine if you put an icepack on your eyes that can actually help clear up your headache faster than possibly taking medication or doing anything else. I thought that was really interesting.

Fiona: Maybe Abigail can tell us what you can tell us what MRI for?

Abby: So when I look at nuclear magnetic resonance, I'm actually looking at real material. So I've done a lot of work with superconductors. So I think there's another episode on Titanium Physicists that's about that. But the idea is that if we had a room temperature superconductor then we could move power from one place to another without any losses. And that would be great because most of the power, where we make it is really far from where we use it the most. And the normal ways we transmit it you lose a lot of the power from where it's being made to where people use it. So we're trying to understand the basic properties of why is something superconducting and could we make something that has a higher superconducting temperature to try and solve part of the energy crisis. So that's sort of what I look at.

[37:50]

Fiona: So Noah, I think you had a question about what's actually being measured. And I'm not sure we actually answered that question.

Noah: Was it, ‘what’s the mechanism that takes this information from these atoms and translates it to something that humans can see.’

Ben: Yeah how do we know when these things are precessing?

Abby: Right so you have a solenoid that’s around your sample or whatever the thing is that you’re trying to measure. So we can do two things with that solenoid. We can send down this RF electrical power. But we can also pick up if there’s any electrical power coming out from the system. So at some point during all of our processes of making all these changes and tilting and everything like that, you’re going to have an induced voltage that comes out of the system that we pick up with this coil and then it comes back, and the computer reads this voltage back and spits it out as a measurement.

Noah: So it’s a bit like the object, whatever you’re looking at, is the transmitter, a radio station, and the solenoid being the radio receiver.

Abby: Yeah.

Ben: Yeah. Do you know how electrical generators work?

Noah: Yeah, like an alternator in a car right?

Ben: Yeah, yeah. So if you have like a coil of wire and you change the magnetic field that’s going down through the middle of the coil of wire that will cause a voltage through the wire. It would cause electrons to flow through the wire. Just like the alternator in the car, you’ve got essentially a spinning magnet and then wires that pick up that change in magnetic field, as the magnet spins near it. And so if you’ve got all these nuclei, these spinning magnets, inside that are all precessing and doing all sorts of jazz, so each of them has some sort of contribution to a magnetic field, as they move around and rotate and realign with the external magnetic field, that changing overall magnetic field is something we can use a loop of wire to detect. Because as the magnetic field changes as they reorient themselves, it will cause a voltage through this coil of wire, and we can detect that.

[39:53]

Noah: Incredible. So if this MRI is so great, how come my doctor doesn’t have one in his office and he only has an x-ray machine?

Abby: So MRIs are kind of time-intensive to run. So we were talking somewhat earlier how it's kind of amazing that you can see anything at all considering there's all this stuff going on. An MRI is a very sensitive measurement in the sense that it either takes a really really long time or you need a lot of sample to do it. So these machines – because a magnet for an MRI costs a lot of money because it takes a lot more technology to build than a normal x-ray would. I think we understand better how to make an x-ray emitting source than we do how to make NMR magnet that is large enough to have a person inside and has enough sensitive to be able to measure what you want. So on the technology side of that, we've been making a lot of headway with 'how do you make better MRI magnets that have more space inside for people.' But since we're still working on the technology it's just very expensive and it's such a specialized skill set to be able to run an MRI; not everyone knows how to do it. But I think there's a lot more research being done on them now in the medical physics community. So I would suspect that they should start getting cheaper and more readily available.

Ben: Is part of it is just that it costs so much to keep the magnet running?

Abby: Yeah because it has to be fed. I guess that's what I tell my parents when I go to work, that our magnets are very thirsty and so I need to go give them drinks. It's got to have liquid helium in it at all times. But that's also something that we're getting better at using on the technology side. So they only have to be filled once every three months with helium and they probably do need liquid nitrogen like once a day. And that takes a decent amount of manpower to have someone come in and do that, otherwise your machine breaks, which isn't fun for anybody. But it's also the technical thing about making a magnet that has homogeneity. We were talking about how inside the magnet you have all these spins and they interact with each other. The only way you can see the interactions of the spins in your sample or in your person is if the magnetic field that you're applying is really homogenous across space. So all of these values in space that you're measuring, it's the same. And that's actually an incredibly difficult thing to accomplish, a very hard technical problem that is one of the reasons MRI costs so much.

[42:52]

Noah: Nice. I have one more question. How small can one of these machines see? It sounds like we're working on the nuclear scale, but can it see something smaller? Can it see the component parts of an atom?

Abby: No, that's not something that we can see. We're just not that sensitive. It's too much energy required to see on that small of a level.

Fiona: If you had a single atom would you be able to pick up a signal from that or do you have to have a bunch of them to be able to see something?

Abby: So your signal size goes like the number of nuclei that you're measuring. And the signals that I get every day in the lab are typically quite small. So the smallest sample size that I've measured is like a milligram or material, and I don't remember how many nuclear spins that is but it's a lot.

Ben: It's like some multiple of Avogadro's number right?

Abby: Yeah exactly. It's like 10^{20} nuclei that you need to be able to make a measurement or something like that.

Ben: So we're detecting or gleaming information about the quantum scale but we're doing it by surveying massive numbers of things right?

[44:08]

Noah: Cool. What are some future applications of this technology?

Abby: That's a good question. So I know one of the things that they're trying to do is try to make it cheaper and easier. So one of the other uses of NMR is in pharmaceutical companies and a lot of chemistry and things like that, where they're trying to look at the structure of the drugs that they want to give people. And that's a pretty complicated problem. So I know at least there's one company that their pipedream of what they wish they could do is make like a tabletop set of measurements where you could do three or four different types of experiments, not just NMR, but NMR and mass spectrometry and all these other fancy science things right on your lab bench; like you can take it to your kitchen counter at home and do NMR on your kitchen counter and a whole bunch of other measurements. But that's also a technically difficult problem to try to make it easier for the drug companies to analyze what they have.

Noah: So I was kind of hoping for something like data being able to scan for life forms on another planet, but I guess that works.

Abby: I don't think we can reach that far with our scanning. We would have to make a much bigger magnet I guess to be able to do that.

Ben: So for the Enterprise to be able to scan things using NMR they would have to build essentially a big ring so that they can pick up changes in the magnetic field and then put up a monster magnetic field around a planet. So it would be even more invasive than just irradiating them with x-rays. Well that was wonderful. Thank you Abby. Thank you Fiona. You've pleased me. You're efforts have born fruit and that fruit is sweet. Here is some fruit. Abby you get a Bartlett pear! And Fiona you get a honeycrisp apple! So Noah, I'd like to thank my guest Noah Zimmerman. Thank you Noah. Did you have fun?

Noah: I had so much fun Dr. Ben. Thank you. Thank you.

[46:09]

Ben: Yeah, thanks that was fun. Alright, it's announcement time. First, I'm still working on getting the *Question Barn* podcast up and running. The first episodes I've recorded sound pretty good so far and I'll probably start posting them in November. If you'd like us to answer your questions please send your questies to Tiphyter@titaniumphysics.com. Second, as I said at the start, I'm going to be attending the Nerd Nite Block Party, for the Bay Area Science Festival in San Francisco this Friday, October 24. We'll be recording *Science…sort of* out of a venue called the Piston & Chain at 6:30pm. If you can make it I'll give you a Barn and the Bunny pin; they're really cute. Okay so third, good news everybody, our Patreon campaign is building. We've reached our first funding goal, enough money to get the current episode transcribed. So I'm getting back in touch with the guy I was speaking to this summer and if everything works out I'll start posting the transcripts on the website. I'll post them under each podcast episode. And I'd like to hear your suggestions about the fun ways we can use this to make the information more accessible. So on that note, I'd like to remind you that we're accepting donations. We'd be grateful to receive your support. You can make a one-time donation using Paypal through our website or you could set up an automatic donation each time I finish an episode using the Patreon website. So that's pretty fun. This particular episode of the *Titanium Physicists* has been supported by a collection of generous people. I'd like to thank Sam and Tony Boge, a gentleman named Josh, another gentleman named Steve, Mr. James Clossin, Mr. Debenorth, a gentleman named Scott, Ed Lollington, Kelly Weinersmith, Joselin Reed, a Mr. S. Hatcher, Mr. Rob Abrazado, and Mr. Robert Steitca. Thanks also to Brent Knopf for remastering our intro. I really appreciate the help. I guess now it sounds less tinny? Anyway, that's it for Tiphyter this time. Remember that if you like listening to shows where scientists talk about science in their own words, there are all sorts of lovely shows on the Brachiolope Media Network. Intro song to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Thanks, and until next time my friends, remember to keep science in your hearts.