Episode 55, Laser Laser Laser Laser Laser Laser
Dramatis personae:
- Ben Tippett
- Aaron Fischer
- Tia Miceli
- Abby Shockley

The Titanium Physicists Podcast
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Ben: Never be afraid. There's nothing which is known which can't be understood. 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 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 Physicists. You're listening to the Titanium Physicists Podcast and I'm Ben Tippett. And now... *allez physique*!

01:11

[Intro song; *Tell Balgeary, Balgury Is Dead* by Ted Leo and the Pharmacists]

01:46

Ben: The movie Austin Powers: International Man of Mystery is perhaps a victim of its own success. It came out in 1997 and was a heartfelt parody of the James Bond franchise of films. And parody is so hard to do well. A superspy is frozen in the 1960's and is revived in the 1990's to fight an old enemy. The movie was a smash hit, not because of its well-written and disciplined humor but because of the style of the thing. Austin Powers brought with it the style of cool mod subculture and the swinging free love of the 1960's and then all the young people were like "Yeah, shagadelic". Weird. Anyway, it was so successful they made several sequels and they weren't very good. So I mentioned before that the humor in the first movie was tight. It was very silly, yes, it was a parody! But, it didn't overlook the little details. In one of the most famous scenes the villain, Doctor Evil, has just jumped to the late 90's and rejoined his criminal organization and began spitballing plans to take over the world. Each plan he proposes is shot down by his employees. The joke being that most of the thing he propose, which by 1960's standards seem horrible, have already happened by the late 90's. So, Mike Myers playing Doctor Evil goes something like "Back in the 1960's I had a weather changing machine that was in essence a sophisticated heat-beam which we called a laser. Using this lasers we punch a hole through the protective layer around the Earth which we scientists call the ozone layer." And of course his employees shoot him down because in the 1980's we had to ban CFCs because they'd already eaten a big hole in the ozone layer. But, thing that makes this scene great is how Doctor Evil explains these things to his employees. He knows they're not scientists so he introduces the technical words by saying them slowly with air quotes. The word ozone is a name of a chemical - rather rare type of oxygen molecule and the word laser is a technical acronym. And lasers were not common technology in the 1960's, they are now, though. And that's the joke! But noticing that lasers would seem anachronistic to time travelers is characteristic of the type of detail which made this parody so tight. Anyway, lasers, right? Laser. It's an acronym: "Light Amplification by Stimulated Emission of Radiation". It's a machine that shoots a really bright dot of light. And unlike, say, a flashlight where the light gets weaker the further you are from it, the laser's dot doesn't seem to get wider or weaker the further you get from it. It stays just as bright! So, how do these laser things work anyway? Today, on the Titanium Physicists podcast we're talking about lasers. Okay, my guest today is a software engineer and a clever and accomplished gentleman. Mr. Aaron Fischer lives in Seattle and has worked for companies such as Intel, Amazon, Microsoft. He currently works at Redfin - the real estate brokerage and technology company. Welcome to the show, Aaron Fisher!

Aaron: Thanks for having me, Ben.

04:42

Ben: Alright, I'm so excited. So Aaron, for you today I've assembled a fantastic combination of Titanium Physicists. It turned out that these two Titanium Physicists know each other unbeknownst to me, back in the day, when I first had them on the show. So, I said: Yes! Let's combine them! Let's make a super pair! Just for you, Aaron Fischer, arise Doctor Abby Shockley!

Abby: Oop! Boop!

Ben: Doctor Abby did her PhD at the University of California, Davis. She's now at the University of Paris, South XI, working *Laboratoire de Physique des Solides*, as a post-doc studying nuclear magnetic resonance. And arise, Doctor Tia Miceli!

Tia: Boing! Boing! Boing!

Ben: Doctor Tia did her PhD at UC Davies and she's currently a post-doc for New Mexico State University, posted at Fermilab, where she's an expert at nuclear particle physics. Alright everybody, let's starts talking about lasers.

05:34

Tia: So, the first thing that we need to understand how lasers work is we need to understand how the energy levels in an atom work. I'm sure you remember what an atom is from like high school chemistry, right? You have a positive nucleus with all of these electrons flying around in clouds outside. So, each of those electrons, you know, they're layered from the inside out and they have different energies. So, the different energies that the electrons have in the atom, they're quantized. So there's a fixed pattern of orbits that electrons can make around the nucleus of the atom. And, it's a fixed pattern because of quantum physics.

Aaron: Everything is discrete, right? So like it jumps up a level, it means that it's further out in the orbit?

Tia: Yeah, exactly.

Abby: Yeah.

Tia: So, the electrons can switch between those different shapes of orbits by having different energies.

Aaron: Yeah.

06:40

Tia: And, so these electrons are only allowed to have discrete energy levels and based on each one you'll get a different orbital shape. And so we need to understand that when you excite one of these electrons and it goes into one of the higher energy states/ When it falls back down, to its home state we will know exactly how much energy is released. And that energy will be released as a quantum of light. It's called a photon.

Aaron: Is this the reverse of this/ the Einstein photoelectric effect? Like, you shine light on something and electrons pop off? Is that/ Can I think of it as/ Can I consider that/

Tia: Yeah, exactly. So, in Einstein's photoelectric effect you shine a certain wavelength of light onto a metal and then it will have enough energy to kick out one of the electrons from a specific energy shell and it becomes a free electron. So in what we're about to talk about, in lasers, we have an excited electron and it will relax into its base state and it will give off a very specific frequency of light. Like, gives of a photon. So, we know that light has both wave-like property and particle-like property. It's something called duality.

08:09

Abby: So this like wave-particle duality of light thing it's/ light can be described as few different things. So like a wave like what you see at the beach, you know. You see waves or standing waves that you can get that from like a slinky if you hold it between two people and start shaking it, you can get standing waves. So light is like that but light is also instead of like a wave, which is a big composite object, is one unique thing that's entirely to itself, though it's a particle as well.

Aaron: So, the duality thing I have tried to wrap my head around a lot and I kind of gave up [laughs].

Abby: [laughs]

08:51

Aaron: The whole thing, like, we have an atom and we have electrons and they get a little excited, jump up a level and then they can't hold it so they drop back down but kick out a photon. And that photon comes out/ like for the purpose of where we're going with lasers/ like, should I put on my wave sunglasses and just think of it as a wave or is it more useful to focus on its particle properties?

Ben: It's both, actually.

Abby: Yeah. That's the tricky thing about light. It's that you have to wear both sunglasses at the same time.

Ben: The deal is, that we knew that light worked as a wave a long time ago. 1800s we figured it out.

09:31.0965

Abby: The particle thing, though, is fairly new.

Ben: That's right.

Abby: This idea that it can be both.

Ben: Yeah, so we figured out that light works like a particle with Einstein's thing you've mentioned.

Aaron: Einstein photoelectric effect.

Ben: Yeah, the deal with that is: you take two different colors of light. One of them is really intense but kind of reddish, the other is really, really blue. Okay? And you tune then so that they have the same energy output. Okay? One of them has energy output in terms of being really blue. The other achieves the same amount of energy by being red but really intense. And if you shine them both on the metal what'll happen is: the one under the blue light, the metal will start spitting off electrons; the one under the red light will not. And when you think about this, it doesn't quite make sense, because they're both putting the same amount of energy into the metal. So why is it that the ones that are blue make the electrons jump off and the ones that are red don't make the electrons jump off at all? It's because, essentially, in light the energy must be carried in terms of little, well, we imagine them as little balls; little particles.

Abby: Packets.

Ben: The energy of each of these packets is determined by what color the light is. So the bluer it is the more energy it has. And so, from the perspective of one of these electrons that's circling and circling the atom, when it gets hit by a little bit of light, it gets hit by one red photon and another red photon and each time it gets hit with one of these photons it looks at it and it says "this isn't enough energy to escape". And just because there's lots of them, doesn't mean that it can use any of them. It's kind of like when you go to a parking meter that only takes quarters and all you have is nickels in your pocket, right? And you're like "I'm putting nickels into that thing and it's not giving me any money", right?

11:18

Aaron: So, exact change is required?

Ben: Yeah, exact change or higher is required. And so, the blue photon comes in and the electron says "this is enough to escape" and it will take that and it will turn it into energy and it will hop off the atom.

Aaron: So, the required energy. Is that dependent on the particular type of atom? Or the electron orbit level? Or is it/ will the red light work in one atom but not in another?

Ben: Yeah, so technically I think it will but it's usually put in terms of a lower threshold. Any light that's higher frequency than a certain threshold will give the electrons more than enough energy to escape.

Aaron: Okay.

Ben: Now, what Tia was mentioning before is the transition between orbitals. Which is to say, right now we've been talking about electrons that are getting enough energy to escape completely, but around each atom, based on quantum mechanics there are different orbitals that one electron can jump between. And going from a near orbital to a distant orbital requires a certain amount of energy which it takes in and then gives off. And those are really, really specific frequencies, okay?

Aaron: Okay.

12:23

Ben: Transition from the first orbital to the third orbital can only be done with a very specific frequency of photon. And so if it has that it can jump between them and if it jumps from the third orbital down to the first orbital it will emit a very specific frequency.

Aaron: Okay. This might be my software side kicking in but can all of these be reduced down to like some multiple integer of the Planck value? Is that the right thing?

Abby: Yeah.

Aaron: Okay. And higher the orbital, roughly, the more/ the higher the multiple.

Ben, Abby: Yeah.

Ben: So this is essentially what other physicists discovered at the turn of the century. They were doing spectroscopy on gases. So they were taking the light emitted by a hot gas, like the Sun, and they were taking a prism and using this prism to split up the light emitted and they saw that, well, if you shone white light through a gas, then the white light

Tia: Sean?

Ben: Yeah.

Tia: Is this some Canadian thing?

Ben: What?

Abby: [Laughs]

Abby: It sounds funny to me.

Ben: If you shined?

Abby: If you shone.

Ben: Shone. Wow, regional dialects.

Tia: Sean is a name.

Abby: Yeah.

Ben: That's great. Okay, I'm gonna stick with shone because that's my regional dialect.

Tia: Oh my God, that's gonna be really confusing.

Abby: It really is. Okay, go ahead.

13:43

Ben: If you take some white light and you shine it through a type of gas that only has one type of atom in it, the white light that passes through/ if you take that white light and you split it up using a prism, you'll see that it's missing some key frequencies. It'll look like the normal rainbow but some/ a little bit of red is missing, a little bit of blue is missing, a little bit of green is missing. And those correspond to the atoms that the light is passing by grabbing, as it passes by, the photons that allow the electrons to transition between states. And so this photon, it will say: "Well, there's a whole bunch of different photons passing through. That one there is exactly the one I need to jump from first orbital to the third orbital. It'll grab it, jump up to the third orbital and then the resulting spectrum will be missing those frequencies.

Aaron: Okay, that's slightly confuses me because previously we talked about the level jump happening/ We didn't give it time bound but kind of momentarily? Like, it wouldn't hold on to it. Can you shine enough light on an atom that it jumps up an electron orbital level but stays there? Like, does it kind of keep it? Or does it always have to emit it, relax and go back down?

Abby: I think it always emits it.

Aaron: So if that's true, then how come the spectroscopy signatures you're describing, wouldn't it just absorb the one particular matching frequency of the photon and then emit it right back out, so you'd still see a full rainbow? Like, it's absorbing it and keeping it, right? Or sending it off in a different direction?

Ben: Yeah. I think that it will reemit it randomly. Which means that they're not reemitting them all at once. There's some kind of timeframe over which half of them reemit them.

Aaron: Okay.

Ben: So if you take this light and you shine it on it it'll heat up the atoms and then turn off your backlight, the atoms will then release these photons. And if you take the light emitted by this and hook it up to a prism, what you see is: instead of a spectrum of light, you'll see these individual lines, corresponding to the atoms reemitting the photons.

Aaron: I think I understand. Like, if the light source is steady, as it is in a case of a star.

Ben: Mhm.

Aaron: Then the atom is grabbing the photons with the matching/ compatible frequency, shall we say?

Ben: Mhm.

Aaron: And it's not necessarily holding on to it but it's temporarily holding on to it enough to disrupt the propagation of the light and the viewer see a missing band.

Ben: Okay, that's right.

Aaron: Okay.

16:05

Ben: It's true that if you have a gas and you heat it up enough, eventually the holes will fill in. If it's in thermal equilibrium and you get something called a blackbody radiation which is continuous spectrum. But, if you have some light that's not the same temperature and you shine some light through it, it will absorb these things. Okay, so we're cool.

Aaron: Yeah.

Ben: Now, there is a quantum mechanical effect called stimulated emission. I've mentioned earlier that what usually happens is the electron in third orbital will decide to go to the second or to the first, randomly. It's like it has a coin that it flips. And then as soon as the coin flips up heads, it goes "alright, I'm going down to the first one, here we go". Throws out the photon, wanders back to the first orbital. So usually that's a random thing - it's flipping the coin. What you can do, though, is if you have one of these atoms where it's been excited, so the electron's up in the third orbital and you send a photon, that has the same frequency as the photon the electron would want to emit if it went back down to the first orbital. Let's suppose that it emits a light blue photon. Okay, going from the third to the first. And then if a photon comes by and that photon has the same frequency, it's the same light blue as the photon it would emit going from the third to the first/

Aaron: Mhm.

17:25

Ben: Then that photon passing through will stimulate the emission. The photon will say "Hey, I'm passing by, why don't you throw up that little photon you're holding and then we can go together". And the electron goes "Alright, I'll throw these two photons together" it picks up the photon it's holding, it throws it, they go off and away and it goes down to the first.

Aaron: Okay. So it's a cascading effect?

Ben: Kind of. Well, it's referred to as stimulating emission. The deal is that on a larger scale, if you have a whole bunch of gas and all that gas they're all excited/ If you emit one photon over here on the right hand side, and it comes in and it's just right light blue, it will hit the first atom, cause the first atom to release its own photon and then there'll be two photons and those two'll come out and those will hit two others and those will release four and that's the cascading effect that you can get. And that cascading effect/ it's the phenomenon at the heart of what we used to make a laser.

Aaron: But if you didn't have the initial blue photon/

Ben: Mhm.

Aaron: entering the system, all the atoms are already stimulated and the system would randomly discharge their blue photon anyway, eventually. Right?

Ben: Yeah. One would randomly emit a photon and then that photon might cause its own cascade, yeah.

Aaron: Yeah.

Ben: So, stimulated emission is really weird. Because it's a completely quantum mechanical phenomenon. The reason it happens has to do with us describing how the electromagnetic wave interacts with an excited atom.

Abby: Aaron, you knew that light was also an electromagnetic wave, right?

Aaron: Yeah, going back to duality, the photon is an excitation of the electromagnetic field. That's one way to think about it?

19:10

Ben: Yeah. So, at the heart of lasing. That's the verb given to this process. It's called lasing after the word laser, stimulated emission of light, what you can do is you can have this ball of gas or something and in one direction you can excite it, right? So, how do the electrons get up to the third level? Something comes by and gives it enough energy. It can be a whole bunch of different things. It can be light, where as we mentioned before, it steals some of the photons passing by to jump from the first to the third level or whatever. You can stimulate it by heating it with something. You can send in an electric current and all those moving electrons shove the atoms and in the process of shoving the atoms as they pass by, the electrons inside the atoms jump to a higher level. There's a variety of ways to do this. And this procedure in a laser, we refer to it as pumping. And what we do is if you keep on pumping the material, if you make sure that most of the atoms in this system are at the higher energy level, you can get a really effective way to get this cascade of one light blue photon knocks off another light blue photon and by the end you get a whole bunch of light blue photons moving out. And usually that cascade would deplete the system and bring everything down to a lower energy level but if you're constantly adding more energy to it, the system will kind of stay in the higher energy level and you can keep cascading the system.

20:37

Aaron: Okay, you're keeping it full, basically.

Ben: Yeah, yeah.

Aaron: Is it accurate to think of this as just the cells in a battery constantly being discharged? Like, I'm charging my cellphone, it's still operating, so it's discharging and charging at the same time but it has a steady state like fully charged battery. Is that not a bad analogy?

Ben: Yeah.

Aaron: Like, I'm just picturing a bunch of atoms sitting there.

Ben: Mhm

Aaron: And each of them is flipping a coin like you said.

Ben: Yeah.

Aaron: Does it matter how much total energy you're pumping into a system? Or does it just have to match the frequency of the blue photon in this case? Like, you can't control the randomness of how frequently it's pumping out, can you?

Tia: So you're asking can we control, you know, how bright our laser is? And we do that by having a more intense or less intense source for pumping.

Aaron: That's the heart of my question. And this is a good software way of thinking about it. Like, if I have a laser that's being driven by just one atom going back to what you said earlier, everything is quantized, right? So everything's just streams. And I'm picturing just a single file stream of blue photons at whatever frequency coming in and there's only gonna be so much absorption and discharge of the resulting light regardless of how many blue photons I'm bathing into the laser so I guess is it only way to scale this thing up? With just more atoms? Or I guess the intensity part of the laser I don't quite understand.

Ben: There's two parts to the intensity of the laser. There's this one that you have a whole bunch of photons, okay?

Aaron: Yeah.

22:15

Ben: That causes it to be more intense. But there's something else. So, up until now our description requires only the particle nature of light. We can describe everything in terms of photons, right?

Aaron: Yeah.

Ben: So essentially your stimulated emission is just like you have a whole bunch of houses on the street and each house has a little kid and they don't know when to go to school and then one kid at the back of the road goes "I'm going to school" and then as he marches down the street all the other little kids join him and are like "Yeah, let's go to school, hooray!" and you end up with a whole bunch of kids moving down, a cascading number of children. Fine.

Aaron: Okay.

Ben: That's still all quantum. That's still all particle nature. The reason we need wave nature has to do with a phenomenon called coherence. It's entirely seen from the wave point of view of light. I'm sure that you've seen a diagram of what an electromagnetic wave looks like, right?

Aaron: Yeah.

Ben: It looks like a sine wave.

Abby: Well, like two sine waves, really.

Ben: Like two sine waves?

Abby: Yeah, cause there's like the parallel and perpendicular part, right?

Aaron: The electric field induces the magnetic/

Ben: Yeah, yeah.

Tia: Yeah, right.

Ben: So yeah, it looks like two sine waves. But essentially, you know, if you look at the electric component of that from the side, it looks like a sine wave. Nice and smooth up and down. That's not really how the light we perceive, say, coming from the Sun or coming from a candle or a light bulb looks. If we were to pause time and take our little pencil and trace what the electric field looks like, it would actually look like a whole bunch of squiggles. There would be no coherent up and down to it. And part of the reason for that has to/ it's kind of like the waves on a beach, right? I mean, you think about a wave in water and you're like "well, it's up and down and up and down" but if you're in a boat, the boat goes up and down based on what waves are passing under it and it goes vavavavwalalal blabla bla, right? There's no pattern to it. And the reason for it has to do with wave interference. The idea is that, okay, each individual photon might be up and down and up and down but all these photons are coming at you in a kind of really disorganized way. And so their waves are interfering with each other and kind of cancelling out the pattern.

Aaron: Okay.

24:22

Ben: And the result is that if you analyze this thing in terms of classical waves you see that the energy isn't being distributed through space in a very efficient way because the signal isn't very coherent. So the thing about stimulated emission of light. So, back to our little atom. Our light blue photon comes through and then the electron inside the atom releases its own light blue photon. Those two photons are gonna march in step. They're going to align up perfectly. Their waves will be coherent, they'll line up with each other.

Aaron: Sorry, I can understand how they're the same frequency but I'm picturing like a three dimensional/ the space around the atom. Like, what guarantees that they're flying off in the same direction?

Ben: Yeah, they're essentially going to stack. This is how stimulated emission works. They end up going in the same direction, they have the same frequency and also have the same phase. They're moving. And so essentially, if you look at it from a wave point of view, your first photon comes in and the result, the two photons it's just like the blue wave is twice as high as it was coming in. So it leaves amplified. It's more than there are just two photons, now there are two photons that are definitely not cancelling out.

Abby: I think that that's more of a practical question about how do we actually design a laser versus how do they actually work on like a fundamental level.

Aaron: Okay.

Abby: 'Cause I think that it would make more sense when we start talking about how we make one. Which is not what we're talking about right now.

Aaron: Okay, sorry for prattling. It's nothing fundamental about the way the photons are being emitted from the atom in the right direction, it's just being emitted and being collected and stacked.

Abby: Right.

Aaron: And that allows for coherence. Okay, so we're stacking the light. Then what?

Ben: I've mentioned before. You have a whole bunch of kids leaving their homes. Essentially it's 7:30 am, it's time for all the kids to go to school, nobody's sure who's the first kid to leave the house as they walk to school. This is an outdated metaphor. Kid's don't walk to school anymore. Alright, whatever.

Abby: Some kids still do.

Ben: You've got a bunch of kids, they're ready to go to school, they see one kid walking down the sidewalk. Instead of all the kids running out of the house and running everywhere they're going to march together. Really tightly. Whaaa. So you end up with this really dense packet of children moving down the street all in one direction.

Aaron: So, we've converted them into a marching band.

Abby: Oh, really? Cause I don't know what's wrong with me... I was thinking about Nazis and I was like, this is a hurtful analogy/

Ben: Nazis! [laughs]

Tia: This was coming to mind too. I was like oh no, we have a bunch of SS-kids now.

Ben: What?!

Abby: Yeah!

Ben: They're just kids having fun. They've just learned that the fastest way to run at school if you're not going to trip over each other, cause they really want to go to school to learn physics. So, the fastest way they can get to school is if they coordinate their efforts and march in time.

Abby: I don't know what kind of kids that you know but I feel like not a lot of them are like "Yee hee, let's go to school today to do physics!"

Ben: Well, that's because they don't teach physics until they're in grade 12. That's the reason kids don't wanna go to school.

Tia: I agree.

Abby: Okay.

Ben: I mean, kids don't wanna wait like, for like half a week for their birthday to arrive, right? How can they wait 10 years before they can learn some dang physics.

Aaron: Without the physics, they don't know how to march efficiently. So it's a bootstrapping problem.

27:56

Ben: Alright, so this is the basic things that a laser brings to the party. You end up with not just light emitted from the system, but coherent light. It's all moving in the same direction, all the light is stacking. And so you can end up with a very bright beam that doesn't kind of interfere its way out of a nice bright tight beam.

Aaron: So, in a wave view it just has a higher amplitude?

Ben: Yeah, sure.

Aaron: Okay.

Ben: Alright, Abby. Tell us how to build one of these things.

Abby: Okay. I guess I'm gonna start with a little bit of trivia that has nothing to do with building a laser. The guy who came up with how we make a laser died this year, like a few months ago, at the beginning of the year, which is really sad and he's now my new hero. Like, he's quoted as saying "you know, I helped invent maser and that was enough for me and a lot of people gone their way and I just wanted to do something else because once you know everything about something you don't need to do it anymore". Like, that's so cool. But so, this is sort of what you were getting at before, how do we get it as a focused beam, really? So, you have what's basically an optical cavity so it's kind of the same thing that you would think of if you were thinking about how a flute works to make music. So, you have a cavity and there are different types of things that you can put into a cavity to be a medium. So, like, the medium that we're used to sound travelling through is air but it can take all sorts of different things, so it can take gases or liquids or solids and lasers are made our all of those things but it's basically a medium for the light to transport through. So you have an optical resonant cavity and on either side of it you have mirrors that are just reflecting this light back and forth until it gets to the correct level to send out. It's laser light that you're used to seeing if you've ever played with a laser pointer.

29:56

Aaron: I have a lot of questions. I don't wanna flood you but um, this is why I really love talking about these topics. Because my career started at an internship at the Lawrence Livermore National Lab and I was there for the dedication ceremony for the target chamber of their National Ignition Facility. This thing had a 192 holes in a three-story sphere and it was a 190 lasers kind of converging on one point and I just marveled at how that could possibly work. And so one of my questions is/ The power level they got this thing up to was like in the terawatt range. And so how can you have a laser that you said has mirrors and the photons are reflected back and forth until I guess they're allowed to move on to a target like how do you not melt the mirrors? How do you/

Tia: So you already answered part of your own question. Cause they had so many different lasers pointing to the same location so all of that energy that they were focusing down to one point was spread out through many optical cavities.

Abby: I think this stuff that's bouncing back and forth within the cavity itself isn't actually the full power that's coming out. So once it reaches that full power it pops out but then there's still light that's trapped inside the cavity. So anything that gets to the amount of power that you're seeing in the final laser product comes out through like the hole that the light is transmitted through.

Aaron: Okay. So I guess the thing I was gonna ask and it may be total silliness is, let's build a laser from just one atom and understand the limits of that. Is there an upper bound to how strong the laser can be? Cause I'm picturing the laser's coming in, they're just/ they're photons so they can occupy the same point in space, right?

Ben: They're bosons!

Aaron: So, they're coming in and they're all the same amplitude, same frequency and can you just infinitely pack more photons in the same space like that? Is it just?

Abby: Yup.

Aaron: That's/

Ben: Yeah, if you want to make a laser that does a whole bunch of intense light for a short period of time, you can open the flood gates/ Before Abby was talking about how we build with like an optical cavity, right?

Abby: Optical cavity, yeah.

32:18

Ben: And so you put your lasing medium in and light inside this optical cavity, you know, light/ photons are bouncing back and forth inside this optical cavity and each time it bounces back and forth it passes through the lasing material. And every time it does that, some new photons join it.

And so it goes from being one photon back and forth to five photons bouncing back and forth to thirty five photons back and forth to ten billion photons. Many, right? I'm not sure if there's an upper limit to the number of photons you can put in there but it's probably very, very high. So if you want to make a laser that shoots an incredible burst of energy all at once, you can just drop one of those mirrors and it will let everything out. But instead what they do is they put a little hole in one of the mirrors, effectively. So that some of the photons are coming out. So what you can get is a big herd of photons is bouncing back and forth inside this cavity but then a steady stream of those is passing out through the hole. To make it so that that steady stream is more intense, you just need a cavity with more and more lasing material in it.

Aaron: Aah.

Ben: That said, is there any limit to the energy you can make with a laser? It's a good question because it's like we said before, when we were talking about Einstein's photoelectric effect, where light comes in and causes an electron to get spit off some material. The deal is that the power contained in a wave of light can be dependent on how many photons there are but also what frequency of photons there are. So, you can probably make a thing that scales and packs a whole bunch of blue photons into one place or red photons, you're gonna have a lot of trouble making photons that have really, really small wavelength, like X-rays. There are technical limitations to being able to build things like that.

34:01

Abby: And I think that was the hardest part when they first started making it. So like it's very easy to get the frequencies on the lower side, so the infrared and the red were the first lasers that we managed to make. But it was much harder to get towards something that was on the blue side of the spectrum or like violet or ultraviolet which they can make now. I don't even know that we're at the limits of what you can do with laser technology right now.

Tia: We should talk about applications now. Because one of the applications was in X-ray death laser, right?

Abby: [laughs]

Tia: We were talking about that.

Ben: Okay, so, the deal is they wanted, the American military wanted to build an X-ray laser so that it could do things like melt incoming nuclear missiles, right? Ronald Reagan was famous for forwarding a project where they were going to put nuclear weapons in space to shoot down other incoming Russian ballistic missiles.

Tia: [hums Imperial March]

Aaron, Abby: [laugh]

Ben: You remember this? It was famously nicknamed "The Star Wars project". When I first mentioned this general topic to Tia, was like "Oh yeah, we can talk about Star Wars" and she's like "What do Star Wars have to do with lasers?" and I was like no, no, not those Star Wars. Ronald Reagan Star Wars.

Tia: [laughs]

35:22

Ben: It was called a/ project Excalibur was the proper name of the thing. So the deal is, the frequency of the laser kind of depends on this stimulated emission. You need a transition that goes from one level to another level inside of an atom and releases the right frequency of light but you also need to be able to pump the system, right? Pumping was an important part of process when we're constantly adding more energy to it, raising the general population up to the energy level, right?

Aaron: Yeah.

Ben: And the deal is, if you wanna make an X-ray, you need an incredible amount of power to pump the system. Way more power than what we usually use. We usually use current or flashing lights of different sorts. To do this, you need essentially the same energy levels that you can get in say, atomic bomb. And so they did this. Essentially they designed the thing. The deal is, you take essentially a tube and inside this tube you put your lasing medium. So, all the stuff that's going to stimulate the emission. But we need to pump that system before it can get X-rays bouncing back and forth, right? So, they wrapped that tube in fissile uranium and then built and atom bomb around it. And so, as uranium goes critical, it releases neutrons and bombards a ton of neutrons into the lasing medium, gets the energy high enough that you can lase X-rays. And so, they were gonna put one of these into space and the idea was it was gonna shoot down any weapons when Ronald Reagan started the nuclear war with the Soviet Union. Luckily, they weren't able to do it good enough to do anything with it. So, the project failed for engineering reasons rather that aesthetic or humanitarian reasons.

37:05

Abby: The scientists could have been just sabotaging the project because they were like "this is a terrible idea".

Ben: Oh, it's a horrible idea.

Aaron: So at the opposite end of the spectrum, we have lasers which is visible light, we have masers which is microwave, can we do a radio based lasers? Is that useful? I'm just curious to know what all the combinations are.

Tia: So I wasn't aware of any radio frequency lasers but I just did a quick google search and apparently you can use radio lasers for skin tightening and fat removal.

Aaron: That doesn't make me skeptical at all. [laughs]

Abby, Tia: [laugh]

Aaron: Sign me up today.

Tia: Oh but there's a YouTube video also.

Abby: Exciting. You know, the different levels of frequency of light that you have are useful for different types of applications. So, like, we have the Blu-ray players, so that's blue laser. It used to be that we only had red lasers and red lasers couldn't do as many things as the Blu-ray blue lasers do.

Aaron: Huh.

38:10

Ben: You know why is it that Blu-ray discs can hold more information, right?

Aaron: Uh, can I make a guess? Is it the wavelength of blue light is smaller than the wavelength of red light?

Ben: Yeah, so essentially your optical disc drive is a whole bunch of little/ they're like indentations in like the reflective material. And so when you shine the laser light and spin the disk, reflected patterns will change depending on what pattern you've punched into it. And the deal is, there's a limitation on how closely together you can put these indentations based on what the wavelength of the light is. So you can't put them any closer than the wavelength of the light. And the deal is that if you wanna put them much, much closer you have to upgrade to a higher frequency, lower wavelength type light and then you can put denser information on it, which is why Blu-ray players have these fancy blue lasers.

Aaron: Alright, okay. Oh, okay, another random question from my field. So, the optical backbone that makes up the Internet and also the idea of optical computing in the future/

Ben: Oh yeah

Aaron: Does that make use of lasers and coherent light?

Tia: Yeah

Ben: Yeah

Abby: Yeah

Aaron: Awesome.

39:17

Ben: The field is called photonics and the idea is instead of having electrons send the signals back and forth, electrical currents, we're going to use light. For two reasons: one, light travels faster than electrons; and the second reason is that when electric current passes through things it heats them up. When light passes through things, it just passes through things. It doesn't necessarily heat up the medium. And so you can have a lot more efficient computing that doesn't heat up so much that also happens faster. At the really large scales, communication systems [are] often built using photonic relays. Um, I'm not sure how far they have come in building photonic computers.

Aaron: Okay.

Abby: Yeah/

Aaron: Very cool. Just another/ They're all related.

Abby: I was gonna say on the quantum computing side I listened to a bunch of talks on quantum computing a lot of people are working on in the basic research side is like microwave cavities and trying to get quantum computers using microwaves, so.

Tia: That would be a pretty large computer.

Abby: I know, I think they'd be huge. I think they'd be like the old supercomputers back in the day when they first made supercomputers and they took up an entire room. I think they're like that size.

Aaron: Very cool.

40:31

Tia: There's a tool that nuclear physicists use to study atoms and to study these atoms nuclear physicists want to/ try to get them to be as stationary as possible. And, you know, usually atoms are bouncing around everywhere, you know, jiggling. So these physicists they use something called laser cooling to slow them down. The way laser cooling works is if you have an atom and you shine a coherent laser on it, if the atom's not moving it will see one frequency of the laser, let's say it's green light. But if there's some atoms that are moving away from the light, you know, you get this Doppler shift, so the light will shift toward the red, the wavelength will elongate a little bit and, like we said, if you shift to a longer wavelength that light has lower energy. So, that also won't excite any of the electrons in the atom. However, if the atom is moving toward your laser light source, then it effectively sees a Doppler shortening of the wavelength. So, that atom will think that the light coming to it is a much higher frequency, it will be blueshifted. And this higher frequency of light has the possibility of you know, exciting an electron and when it gets reemitted, it'll emit it out in any direction. So after many iterations of absorbing and reemitting photons you can effectively slow down an atom in one direction. So in order to slow down the atom in all directions, you need lasers pointing from all different directions onto your sample so then you can slow it down to be able to do your studies.

42:36

Aaron: So I think I remember reading some article that said they created the lowest temperatures ever in the Universe by doing precisely this.

Tia: Mhm.

Aaron: You're starting with a frequency of light that's outside the natural absorption window for the atom in question at rest and so when the atoms eventually do settle down, the light is just like passing down over them with no interaction, is that the end state?

Tia: Yeah.

Aaron: So, motion is related to temperature, right? So, like once it achieves the end state, the photons passing over/ it's not heating it up in any way and thus increasing the temperature it just passes through it harmlessly.

Tia: Yeah, that's right because those wavelengths of light, they can't excite anything in that atom. That atom is completely blind to it.

Aaron: That's really cool.

Abby: The chemistry Nobel prize and the physics Nobel prize this year were both about light and they were both about lasers.

Ben: Nice.

Abby: And also this is the international year of light.

Tia: Which is apparently a big deal in Paris, Abby?

Abby: Yeah, well, in my building everybody is always really excited about these international years of insert science topic here. So last year was the international year of crystals and this year is the international year of light. And so they were having celebration in a City of Light because it's Paris and they like to talk about that I guess.

Aaron: I've one last question on the applications side.

Ben: Yup.

Abby: Yeah

Aaron: It might just be a yes or no answer. Um, but so in astronomy they will shine like a really bright laser up into the sky/

Ben: Yep.

Aaron: To help them like normalize the light they're seeing. You know what I'm referring to?

44:22

Ben: Yeah, yeah. Um, I think they use it in part to tune their adaptive optics systems. The deal is there's a lot of astronomy going on and it's fantastic but sometimes it needs to compensate for the fact that the atmosphere gets in the way. And so sometimes a really helpful way to gauge how much moisture there is in the atmosphere and how much you need to compensate for it/ You shine a bright laser straight up and then measure how much it gets reflected back and that might be an indication of how much moisture there is and that tells you how to tune the mirrors.

Aaron: That sounds like a very cool application of lasers.

Tia: Can I list my favorite application for lasers?

Ben: Yeah, go ahead.

Tia: Okay. Sharks with freaking lasers strapped onto their heads.

Ben: Okay, what kind of fruit do you guys want?

Tia: Mango.

Ben: Tia you want a mango? Okay, hold on. Where's my thing. There it is. No, that's not it. Oh jeez, buttons. Nope. There. And Tia gets a mango. Mango. Abby, what do you want?

45:46

Abby: A kiwi?

Ben: Alright.

Tia: Maybe Aaron wants some fruit too.

Aaron: I thought that's not the rule

Ben: The guest gets to eat a fruit of knowledge. And the physicists get to eat the fruit that I give them. It's like a lasing system here. I'm feeding you/ I'm pumping you guys with fruit and you're outputting the fruit of knowledge.

Tia: Wow.

Abby: Then maybe you should give us the fruit at the beginning of the show instead of the end.

Ben: You've only just now depleted your reserves of fruits of knowledge. Which is why I'm giving you fruits at the end.

Abby, Aaron: [laugh]

Ben: Well, that was wonderful. Thank you Tia, thank you Abby. You've pleased me, your efforts have borne fruit and that fruit is sweet. Here's some fruit. Tia gets a mango!

Tia: Nom nom nom.

Ben: And Abby you get a kiwi fruit.

Abby: Yum yum yum yum

Ben: I'd like to thank my guest Aaron Fisher. Thanks Aaron, I hope you had fun.

Aaron: I had a blast, thank you Ben.

Ben: Alright, fantastic.

46:45

Ben: Alright. So, it's announcement time. First I hope you're enjoying the Question Barn episodes. They're a lots of fun to make. I make them whenever I can. And so if you'd like us to answer your questions, please send your questees to tiphyter@titaniumphysics.com. Second good news, everybody: our Patreon campaign is going really, really well. We're building up all of the funds needed to start transcribing the shows. The transcriptions are being made as we speak and every time we record an episode, we put enough money away to transcribe one or two episodes. It's wonderful. If you've got any suggestions for things we can do once we've transcribed all the episodes, including making an app or building a database or whatever, maybe a wiki, send your suggestions my way. On that note, I'd like to remind you that we're now accepting donations. We'd be grateful to receive your support. And you can make a one-time donation using our PayPal through the website or you can set up an automatic donations each time I finish a proper Titanium Physicists episode, just like the one you've heard, through the Patreon website. This particular episode of the Titanium Physicists has been sponsored by a collection of generous people. I'd like to thank the generosity of a man named Guy D., a lady named Elizabeth H., Anthony and Sam Bougue. I would also like to thank a Mr. John Keese, a Mr. Victor C., Ryan Close, Peter Clipsham, Mr. Robert Halpen, Elizabeth Theresa, and Paul Carr. A Mr. Ryan Noule, Mr. Adam K, Thomas Sharay and Mr. Jacob S. There's a good gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Josh and Steve, Mr. James Clawson, Mr. Devin North, a gentleman named Scott, Ed Lowlington, Kelly Wienersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Aberzado and Mr. Robert Stietka. Thanks also to Brett Knob for remastering our intro, I appreciate the help. Now, that's it for Titanium Physicists this time around. Remember that if you like listening to shows made by scientists where they talk about science in their own words, there are lots of other shows on the Brachiolope Media Network, so go to the Brachiolope Media Network page and you can see all of these or you can click the button. We have a special section in iTunes in the Podcast store. So, the intro song to our show today is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. So good day, my friends. And until next time, remember to keep science in your hearts.

49:36

[Outro song; Angela by John Vanderslice]

50:21

Aaron: So, what makes the difference between an object surrounded by lasers, like the National Ignition Facility example I cited, imparting heat vs. the same object shone by lasers that just don't impart heat but reduce the motion. Is it just frequency?

Tia: It's/ It's/ Yeah, it's based on what frequency. So you have to tune up the atom you're studying and choose the right frequency for your laser light based on what you wanna study about the atom.

Aaron: So there's no way you could use laser cooling to arrest the motion of anything that's not like a pure like molecules or something?

Tia: Oh, yeah. Molecules have really complicated electronic structures.

Abby: Structures.

Aaron: What's that Bose-Einstein condensate? Is that created from laser cooling?

Abby: Yeah, so that's basically what the cold atom research is about.

Aaron: Okay.

Abby: So like you have two different types of states that your things can be in. So you can either have a fermion or a boson. So fermion is like an electron. Where, like, if I have one electron that's like an up electron, another electron can't be in the same place as that first electron, so that's a fermion. And then you have like levels of states that you can fill because you can't have two/ more than two electrons in the same place, cause they don't like that. But a boson isn't a/ doesn’t have the same restriction. So a boson, like Bose-Einstein condensate, says that instead of having/ so, the thing I was talking about the electrons - Pauli exclusion principle - that you can't have two in one state, a boson you can have as many as you want and a Bose-Einstein condensate, you can have as many things as you want, all on the same bottom level, you're not restricted to just two. Yeah, and I mean that's the main difference, I guess.

Aaron: Okay. But like before when I was asking how many photons can you pack in the same space.

Ben: Yeah, photons are bosons.

Abby: Yeah.

Aaron: Bosons.

Ben: So they work/ I'm not sure how you call the light coming out of laser/ Can you think of the of light as a Bose-Einstein condensate but they are bosons. We're taking advantage of the boson nature of light doing that.

Aaron: Uh, last question on this. The Bose-Einstein condensate is a type of matter or class of matter? Is that only achievable with laser cooling? Like, it doesn't happen naturally anywhere else in the Universe?

Abby: It does, so there are some other things that form Bose-Einstein condensate. Like, superconductors and it's like lowest state is sort of that same type of thing. It's a very special and very unique class of things that can happen that not a lot of materials can make. So this is laser cooling with a Bose-Einstein condensate, that's a very special unique case. I would say.

Aaron: Okay.

Ben: Yeah, a long time ago we did a show on a super, supercool/

Abby: Oh, yeah, liquid helium does that too, I forgot it.

Ben: Yeah, it's a superfluid, superfluid helium is a Bose-Einstein condensate.

Tia: Superfluid helium kills me every day.

Ben: Every day it kills you? You should be more safety conscious.

Abby, Aaron: [laugh]

Aaron: Okay, uh, very, very awesome.