MICHAEL SHORT: I wanted to give you guys a survey of radiation utilizing technology and tell you a little bit about the way this department has changed the way it teaches. It used to be in our department and probably everywhere else around the country that first we teach you the theory of how things go down and understand them, and then we can teach you the context in which they're placed. This resulted in a rather boring curriculum, in my opinion, having been one of the ones that went through this actual curriculum. So for those who don't know, I was an undergrad in this department. And while I learned a lot of great things from folks, I also kept some mental notes on what I would do differently, and now's the chance to do this.

So instead, we've adopted a context first theory second approach, which means we tell you where we're going to show you why should you pay attention to the rest of the semester. Then we fill out the rest of the theory and fill in the gaps and then revisit the context to show you what you've learned and how you can understand it. That's why today is going to be a rather light class. So don't take any notes, just listen, enjoy, ask questions. And I'm going to show you some of the applications where we use radiation and the principles of NSE and technology today.

And for recitation today since we haven't gone over any technical material, we're going to be heading to my lab to demonstrate one of these things, a sputter coder which is a controlled system for radiation damage which applies one material to the other via the process of sputtering or actual nuclear or ionic collisions that blast material, in this case, gold, onto whatever you want to coat, which in this case is a pile of pocket change. So we're going to make some gold change today.

So the motivation today is really to get over two questions is how can radiation be used for benefit and what is the physics behind how it can be used? I'll be using a zircaloy fuel rod, the same kinds that you'd see in a nuclear reactor as the pointer because I'm not a fan of lasers. And this is actually incredibly light. I can hold it out at the end, not much visible shaking and I wanted you guys to see and feel and try and bend what zircaloy actually is like. That's a piece the same diameter and dimensions and stuff that you would see in a nuclear reactor.

So give it a slight bend. If you try really hard, you can bend it. But notice how light it is. Notice how strong it is. It's about midway in density between stainless steel and aluminum, but it's a hell of a lot stronger than aluminum. It also has the added benefit that it basically doesn't absorb neutrons. The real reason we use zircaloys, zirconium alloys and reactors is that they have very low interaction probabilities or cross-sections. And for those who don't know what those are, in a couple of weeks we'll be defining what a cross-section is.

This stuff's pretty cool. Also what makes this nuclear grade zircaloy and not just regular zirconium is that there's no hafnium in it. Hafnium is chemically very similar to zirconium, it also happens to be one of the highest cross-section elements that there is. So you hide the stuff that you need to be neutronically transparent in reactors. It happens to be found in the ground with the last thing you'd want in your fuel cladding. In fact, you can use hafnium as a control rod or control blade.

So the difference in chemistry and in cost between nuclear zirconium what you've got there, and regular zirconium is the hafnium has been taken out by some very painful chemical separation. Usually you'd find about 3% or 4% hafnium. So there's all sorts of technologies that we use, the principles of nuclear science and engineering. I'm just going to say NSE from now on.

You're all probably pretty familiar with power and maybe familiar with some of these other ones. Like medical isotopes are the backbone of a lot of imaging techniques to find and treat different maladies. Space is basically a giant maelstrom of radiation so you can both use it and have to shield from it. We'll go over some of the crazier ways of shielding from space radiation, actually today.

Semiconductors. The way that the MIT reactor made about 60% of its operating budget until recently was by irradiating crystals of silicon single, crystal bools or ingots of silicon, to make what's called an n type semiconductor, via the following reaction if I can find an eraser. I'm going to use the shorthand that we talked about last time. Normally you would take silicon and you add a neutron and you end up forming phosphorus.

I've not memorized the masses of the isotope, but in the end this is actually a neutron capture reaction, and then a resulting decay, which produces phosphorus, which is what's also known as an n type dopant. It's a sort of extra negative-- what is it? --a negative charge type dopant that changes the conductivity of the semiconductor.

There's lots of different ways of doping semiconductors. One of the best and most uniform is to stick things in the reactor. So back when silicon ingots were smaller, like 4 or 6 inches in diameter, there was a constant train of these things traveling through the reactor getting irradiated and being sold and then cut up into wafers to make devices. And it used to be students or Europe jobs to load and unload those things from the reactor.

Now, it's not that dangerous. As long as you use the right handling procedures, like put them on a cart, pull the cart at arm's length and push like that, your dose is very low. And that's because for a given point source emitter, the dose you receive drops off as 1 over r or the distance squared, which means that your arm's length, let's say your arm is about a meter, you can drop the dose by quite a bit compared to what's called the contact dose.

Well, this poor fool held the silicon ingots up to their chests like that. They were OK. They got about 10 months of their yearly allowable radiation dose that won't induce any additional risk of cancer. But to ensure that they would not exceed that allowable dose, they became the administrative assistant for the reactor for the next 10 months. So their job at the reactor was to answer the phone, which is not a radioactive activity, including at the reactor.

First nuclear power. The reason why I know a number of you guys are here is pretty simple. It's just a hot bucket of water. The way we make that bucket of water hot is by putting uranium or other fuel into these rods assembling a lot of them in a small space where they then heat up by producing nuclear fission, capturing the resultant kinetic energy of the fission products and neutrons and everything else that comes out and using it to either heat up or boil water, that's then just driven through a heat exchanger and a turbine. So aside from everything on this side, it looks basically like any other water cooled power plant. The difference is things get toasty in a radioactive sense, but also pretty well under control.

And what's inside a reactor-- if you say this is the diagram of a typical Pressurized Water Reactor or PWR where the water is pressurized enough so as to stop boiling from occurring, keeping the water liquid which has a number of safety implications, you've got the core of the reactor right here-- and these things right here are called steam generators. It's nothing more than a heat exchanger that generates steam. --and the steam generated in here goes off somewhere else and drives the turbine. If you look inside this reactor you'll notice a lot of different fuel assemblies or fuel rods, including things like control rods or shut down rods, rods made of neutron absorbers like hafnium that we talked about, or gadolinium or boron 4 carbide or any other material with a high capture cross-section, meaning a high probability for capturing a neutron rather than letting it go from one fuel element to another to produce more fission, to produce more heat. That's effectively how a reactor works.

So we went over a little bit about the fuel. The fission and the energetics is kind of cool. So let's say you start off with uranium, probably the fissile isotope 235, and you send in one neutron-- think it's 92. Don't quote me on that though. --and instead of undergoing some sort of a capture reaction or something else, it can split into what we call different fission products. And plus, anywhere between two or three neutrons the usually accepted number is an average of about 2.44 neutrons plus gamma rays, plus antineutrinos, plus other energy and some occasional other stuff.

The main point here is these fission products-- if let's say you had a uranium nucleus and it were to split in half, fission products go in other directions, they carry with them quite a lot of kinetic energy. And what we'll be doing a lot in the second half of this course is watching to see how do these highly energetic nuclei or atoms-- when they slam into other atoms, how quickly do they lose energy? How far do they tend to go? These fission products tend to stop in the fuel.

Their range is going to be on the order of nanometers. I don't even think it reaches microns. But the neutrons however, as we saw from looking at Chadwick's paper, they can go pretty far, usually on the order of around 10 centimeters in a reactor before they go do something else. So it might make it a few fuel rods over, and chances are get captured by another uranium nucleus making more fission, more neutrons, and some other fun stuff like gamma rays and neutrinos.

Anyone not know what a neutrino is? So a neutrino is a very, very low mass but not massless as was found I think like last year; almost speed of light particle that's released as part of radioactive decay. They basically don't interact with matter, but once in a while they do. What that means is that they travel straight through everything. It's been estimated that trillions of neutrinos from space are passing through us per second and on average you won't get a single interaction during a day.

In fact, to detect neutrinos they've had to fill old hollowed out salt mines with water and fill them with photo tubes in the hopes of catching two or three a day. What that means is if someone turns on a reactor somewhere anywhere in the world, it's releasing tons and tons of neutrinos and if all of a sudden you start to see two or three coming from the same place, that's a rare event. That's something with some statistical significance. And there's been projects in our department using neutrino detectors to try and detect where reactors are turning on anywhere in the world.

So we've been able to sense that the MIT reactor is next door from the building next door. I don't know how well this is going to work when you get to farther distances. But the physics is pretty much there.

It's an engineering problem to figure out, well, how do you detect enough neutrinos to get a statistically significant signal? That, far as I know, has not been solved. Hopefully, by this time next year it will.

There's also control rods-- rods filled with absorbers, like I mentioned before. If you want to stop this nuclear reaction, you send in something like hafnium or gadolinium or boron. So let's say, Boron-11, like Chadwick knew, would be able to capture a neutron. And then it would turn into-- what's the next one over? Well, sorry. That's a one and a zero. That's a five. That should turn into carbon-12. And then you've captured the neutron instead of letting it get into more uranium and cause additional fissions.

So when something's going wrong, or you want to control the power level in the reactor, you insert control rods. They soak up the neutrons, and make the reactor go subcritical. And we'll go over what all these words mean in due time-- various points in the course.

There's also coolant and what's called moderation. Does anyone know what I mean by moderation of neutrons? Yeah? What do you mean?

AUDIENCE: It thermalizes them.

MICHAEL SHORT: It thermalizes them. And in other words, it slows them down. Because the probability that each uranium nucleus can capture a neutron depends on the energy of the neutron.

The cross sections for interaction, which we give the symbol sigma for the microscopic or sort of mass independent cross section, they're functions of energy. They're extremely strong functions of energy, over the energy ranges we're interested in. Because we're interested in an extremely large energy range.

These neutrons tend to be born at around 1 to 10 MeV, or Megaelectron Volts. And by the time they thermalize, like you said, or reach roughly room temperature, kinetic energy is of about 2,200 meters per second, they can be-- what is it-- a 40th or 0.025 eV, fraction of an electron volt.

So we're interested in nine orders of magnitude of energy. And the cross sections vary wildly over these nine orders of magnitude. And I'll show you what some of these look like pretty soon.

And in this case, in the case of light water reactors, like the PWR we saw, the coolant and the moderator are basically the same thing. You guys remember how when Chadwick put the paraffin in front of the neutron source, he started to see more ionizations. That's because the paraffin is a great source of hydrogen. So is water.

Water is an ideal coolant because it takes a lot of energy to heat it up, and a lot to boil it. So you can store a lot of energy with less of a temperature difference in water. And it's full of hydrogen. And kinematically, it's easier for something the size of a neutron and the mass of a neutron to slow a neutron down.

Because a neutron hitting a proton can transfer up to all of its energy ballistically. Then that proton won't move very far because it's also got charge on it. If a neutron hits something heavier, like stainless steel or other stuff in the reactor, it cannot, by conservation of energy and momentum, transfer all of its energy. That fraction is actually pretty small. So you'll see. We'll actually calculate what that fraction is. But it drops off pretty precipitously as you start to get heavier than hydrogen.

And finally, there's reflection and shielding. We'll get into shielding in terms of how much stuff and how much matter does it take to stop radiation from getting through. In some cases, you can stop it all.

In some cases, like gammas, you technically never can. You'll just get what's called attenuation or continuous removal of gamma rays. But chances are, you can't remove every single photon from getting out. It's only a matter of how much do you need it to get down to.

And there's a neat aside. Who here has looked down into a nuclear reactor before? Three of you. Wow. Four. OK. What did you see?

AUDIENCE: Not that much.

MICHAEL SHORT: Not that much. This is a particularly powerful reactor known as the Advanced Test Reactor, or ATR, at the Idaho National Laboratory. You won't see any others that look like this. One, because these crazy-shaped fuel elements are not that easy to make.

This is a test or a research reactor where things get irradiated. It's about 125 megawatts. And the blue light being produced is called Cherenkov radiation. It's from electrons and things moving, or beta particles, electrons, moving faster than the speed of light in water.

Now, as you know, you can't exceed the speed of light in a vacuum. But things can move through other media faster than the speed of light in that medium, effectively producing optical shock waves given off as little blue cones of light for each particle. So when folks say, oh, am I going to go green when I get near radiation? You can say, no, you'll glow blue. They've just got the wrong color on all the TV shows.

And then onto fusion energy. Since most of us tend to talk about fission a lot of the time, but how many of you here are interested in going into fusion? Usually, it's at least half the class. And so I figured this used to be a fairly fission-centric teaching style in the department.

And I think fusion deserves equal time. Because about an equal number of you want to go into fusion to make it a reality. These reactors are laid out fairly differently.

What they'll be is a big, hollow vacuum chamber that's shaped like a donut or a torus, and lots of magnets to confine a plasma or sort of a charged mess of separated ions and electrons that whirls around in millions of meters per second.

Once in a while, these ions and electrons, or especially these nuclei, will collide with each other and undergo a fusion reaction, or one of a few fusion reactions that I've written up here for you. So in this case, there's no elements with a symbol d or t. We're just using those to refer to deuterium or tritium as a visual aid.

But you should know that they're deuterium and tritium from their atomic numbers. One, which means it's an isotope of hydrogen. And their mass numbers, two and three, which is not the mass number for normal hydrogen.

And in this case, when you fuse deuterium and tritium, you can produce helium and another neutron. And so then those neutrons can be used to hit lithium, which they'll usually have in what's called a breeder blanket around the outside, which releases more tritium.

So fusion reactors actually can produce their own fuel. The trick is they're radioactive gases, so containing them can be kind of tricky. You also need a way to get the helium out of the reactor.

But we have one of these on campus. We have one of the only three in the country. It's called the Alcator C-Mod. Have any of you guys seen a tour of this place yet? Almost all of you. So for ever who hasn't, do it this year. Because this may be the last year of Alcator C-Mod's operation.

That's not to say there won't be the next fusion device on campus, but there's one here right now. And it might be a while before the next one's built. So if you haven't seen it yet, go and see it this semester, definitely.

The reason why fission and fusion work from an energetic standpoint, is if we look at the binding energy per nucleon-- remember, last time we mentioned the binding energy is the difference in energy. If you were to take, let's say, a proton and a neutron from infinitely far away, and bring them together to create a nucleus of deuterium-- we'll call this D-- these two, the energy of the proton plus the energy of the neutron, the rest mass energies, rather, would be greater than the energy of just deuterium. And that little bit of mass that's changed is converted into energy. And this is what's known as the binding energy.

If we look at the binding energy per nucleon or per proton or neutron, we can get a relative ranking of how tightly bound each nucleus is. So for the light isotopes, smashing them together should liberate excess binding energy-- or sorry, excess energy-- because you'll gain back some of that energy by the conversion of mass to energy.

Same thing over on this side, just not as extreme of a gradient. If you were to split apart heavy nuclei, like uranium-235, you can release a little bit of energy in fission. And once you get up here to iron, you can't go either way, which is why, if you think about the biggest fusion reactors that exist in the universe-- anyone know what they are?

AUDIENCE: Stars.

MICHAEL SHORT: Stars, right. They tend to hit cores of iron before they either die out or go all gravity crazy and become black holes of supernovas, or whatever you will. This is kind of the energetic limit for normal nuclear processes. Or if they become a neutron star, then things get beyond the scope of this course. I won't be explaining neutron stars.

There's a lot of medical uses of radiation. I don't know if any of you guys have seen these things. It's the only time I'll show a tricky looking biology diagram, because it's kind of interesting to note.

These are what's called brachytherapy seeds, little seeds of isotopes that remit a certain type and energy of radiation selected for their applicability, that can be implanted in the body at the site of a tumor to deliver localized radiation treatment. You can either go in through existing ports on the human, and not having to drill or cut a hole in someone, or they can be implanted laparoscopically or surgically.

So this way, if you don't want to subject someone to a whole body radiation dose or chemotherapy, or if you want to use it in conjunction with chemotherapy, you can implant a tiny little seed of a radioactive material in there to deliver a certain dose to a tumor, and then take it out.

And that way you know very, very well what the dose is going to be, because you can measure the activity or the number of decays per second of that brachytherapy seed. And you know how it's going to change over time. Because you know the half-life of the particular isotope that you've looked at.

There's also things like imaging. You can have someone ingest an isotope like technetium-99 metastable, to highlight certain organs or things in the body that you can then image later by their decay gamma rays or other phenomena.

It's also one of those reasons why when you go in an airport, you have to tell them if you've had a medical imaging procedure. Because a lot of these places have radiation detectors. And if you are radioactive and don't identify yourself, you will quickly be identified and taken into the back room to the probulator, or whatever they're going to do at the airports. I don't know. I've never been searched I don't plan on that happening.

There's also X-ray and proton therapy sending in well-known, well energy-characterized radiation to fry tumors or other things. In the case of X-rays, you're relying on what's called exponential attenuation. If you look at the distance into a material, and you look at the intensity of the X-rays-- say, at x equals zero, this is your X-ray source. This is your incoming intensity.

It falls off exponentially with distance.

You might then ask yourself, all right, if my tumor is this deep, and I apply that radiation dose to the tumor, what about the rest? What about the part of the body that the X-rays have to travel through in order to get to that site? Anyone know how you would deliver more X-rays to a tumor than the surrounding tissue? Anyone have any ideas? Yeah?

AUDIENCE: Go from different angles so the rays intersect on the tumor.

MICHAEL SHORT: Exactly. Go from different angles so the rays would intersect on the tumor. I'll have a better diagram, but I'll draw one for now. Let's say, that's the eyes and that's the tumor.

You can wear this helmet where X-rays can come in from all different angles. And the X-ray emitter would have to come in from different angles, so that as all the rays intersect, this part gets fried the most, while keeping you from getting too much radiation to the rest of your brain and ceasing to function. There's also radio tracers. I think I already covered those.

So imaging, we already showed an image of what this looks like. The first X-ray back in 1895 didn't have that good resolution, but it was kind of striking in that you could see the difference in contrast between bones and tissue.

I should replace this with the X-ray of my foot that was my signing bonus at MIT. My first day on the job I went down to clean one of the old rooms in Northwest 13, which is now where my labs are. And I moved a bunch of boxes aside, and a 200-pound steel plate, jagged cut with plasma torch, went down and smashed down on the bones in my foot.

And I had one of those temporary feats of superhuman strength and was able to lift it up. I went back to try to lift it up and couldn't move it an inch. I don't know how I got out of the plate. The next thing I remember, I was crawling up the stairs to go to the hospital.

But I did get an X-ray, and they were able to sense that the pain in my foot was due to a hairline fracture. It was like a fracture in the bones that basically came back together. But the improvement in contrast resolution in X-rays is what differentiates the ability to see a hairline fracture from just the ability to see that you contain bones.

And the reason for this, and we'll be looking at a lot of these curves in this course, is the differential absorption or attenuation of X-rays, or any photons of any energy through different types of matter. And so, for example, here we have the ICRU standardized average soft tissue attenuation, as well as bone.

And you notice that there's a few differences in these curves. So also, there's some similarities. I'll note that these actually have the same access to the same units. What do you guys notice that's the same about these curves?

How about the value? They're basically the same-- mass averaged with very little differences. If you look at where it hits the y-axis, about 3 times 10 to the 3rd, 3 times 10 to the 3rd. The curves follow basically the same shape. What's the differences? So Sean, what do you think?

AUDIENCE: Oh. That little jagged [INAUDIBLE] out there.

MICHAEL SHORT: These jagged edges right here. Anyone have any idea why? And these reasons go back to what you learned in high school in 8.02 in terms of atomic transitions, not nuclear.

Anyone here remember the k lines or the l lines? Or what was it-- the-- which emission series were they called-- the different emission lines that you can get from emission or absorption spectra? It all has to do with allowable electron transitions. And notice the units here are in centimeters squared per gram. What's the main difference between soft tissue and bone?

AUDIENCE: Density.

MICHAEL SHORT: Say it loud enough so I can hear.

AUDIENCE: Density.

MICHAEL SHORT: Density. Bone tends to be a fair bit denser than soft tissue. So these are mass-- what is it-- mass normalized curves. But the fact is, if you have a bone that has a higher density, then you're going to end up with more absorption.

In addition, you can use some of these features and differences to your advantage. Like, if you choose a photon with energy here, it might not be nearly as absorbing in soft tissue as it would in bone. So by selecting the mass of the thing you're trying to image which you don't control, and the energy of the photon which you can control, you can produce as much possible contrast as you can between two different things.

Is everyone clear on how that could work? Cool. We'll be going over why the curves have these shapes, especially these jagged edges pretty soon.

And like you said, this is how you irradiate a tumor with X-rays. Because you can't quite control the amount of dose to any one part unless you split it up into a whole bunch of different rays.

Proton therapy is quite different. It's a newer technology. And it relies on very well-known and distinct ranges of charged particles to enter the body with very little damage, stop and do their damage in the tumor, and not come out the other side. They just require significantly more expensive hardware.

There's one of these at Mass General Hospital, or MGH, down the road. It consists of a cyclotron or a particle accelerator, which injects and speeds up protons so that they're moving very fast, then sends it in a beam through a bunch of bending magnets and up to deliver the protons to the patient.

The way this works is you start injecting the beam. And as it goes through these two magnets, or what's called dees, every time it moves through the magnet, it's a charged particle and a magnetic field. It has a fixed curvature.

But every time it's accelerated through this electric field it speeds up, so the curvature gets greater and greater and greater. And it spins outwards in a spiral until they exit the beam. And by deciding how long they get to spin, you get to choose the energy of the protons.

Why does proton therapy work? This has to do with a difference in interaction between charged particles and photons, which have no charge. Charged particles will lose their energy in a very well-known way, what's called the stopping power formula, until they actually stop in the matter that they are going through. Photons either scatter or attenuate, or they don't. And you can't stop them all.

So I want to run a quick Monte Carlo simulation for you guys, and show you what protons stopping in matter looks like. So this is a program called SRIM, or the Stopping Range of Ions and Matter. It uses the formulas that we'll be deriving and developing in this class to calculate the trajectory of protons in anything.

So let's say, you are made basically of water. So let's say, you consist of hydrogen and oxygen in a stoichiometric ratio of two to one. I think water approximates humans pretty well. So we'll find out what the range of these actual protons is in humans.

So what we do know is that it's a proton accelerator. And I know that the MGH accelerator has an energy of 250 MeV, or 250,000 kiloelectron volts. And finally, we decide how thick is the person? So how thick is a person, typically? How many-- what units do we get? How many centimeters thick is the average person?

AUDIENCE: Forward or from the side?

MICHAEL SHORT: Let's go the shortest distance in, so front to back. Maybe 10? Right? 10 centimeters? Not that much? Can it get halfway through you? Only has to go halfway, because you can always lie in your stomach. All right. Let's go 10 centimeters.

Most of the protons go screaming right through you. You notice they don't actually stop in the person. So you don't tend to irradiate people with 250 MeV protons directly. You'll actually slow down their energy to something a little more reasonable, maybe 50 MeV.

And then you can actually watch each of these charged particle tracks being computed. As it hits, let's say, imaginary nuclei or electrons, the paths will be slightly deflected. But what's really striking is they all tend to stop at about the same place.

That's the really cool thing about charged particle interactions, is if you know the charge, you know the nucleus, you know the energy, you can calculate the range to within a very narrow margin. And what this is doing is just flying. Looks like it's done 70 ions so far. And it will keep on flying them until either you hit the end-- let's say, we set it to do 100,000 atoms-- or you just tell it to stop.

Also, when you don't have to draw the lines, it goes way faster. So let's let it get maybe 300 or 400 ions, and we'll show you what the average range of the protons looks like. How far do they go before they stop?

If we look at the ion distribution it's pretty striking. All of the protons, except it looks like one of them, stopped at a very fixed depth of 41.9 millimeters with very little straggle, maybe 0.6 millimeters on either side.

So depending on the depth of the-- you can even get a deep, very shallow, very small tumor if you get the distance just right and the proton energy just right. This is why proton therapy centers are popping up all over the world. This is a much more effective, though expensive, treatment for certain types of tumors.

At the same time, since we're nuclear engineers, we may be concerned with the amount of radiation damage being done to different materials. And so this is kind of a measure of how much energy the protons are losing as they travel through. Notice, it's not zero. As soon as the protons enter the person, they start to scatter around, undergoing some different interactions.

But they mostly don't lose much energy until they reach almost their target depth. And what's called the stopping power is very low at high energies, very high at low energies, which means once they get slow enough, they almost all stop right there at what's called the Bragg peak.

And that's the basis behind proton therapy. And you'll be able to understand why every feature of this curve looks the way it does by the end of this course-- probably by the end of this month.

So let me stop that simulation because we really could go on forever, but we won't. Then the question is, what do you do if the tumor is too big? If the tumor is larger than that straggling, you actually have to sweep the energy of the proton beam.

So you can vary the energy continuously in what's called intensity-modulated radiation therapy, where you change the energy of the proton, sweep it back and forth across the tumor to cover the whole thing. So you can sweep out in 3D space the size of whatever you want to die, without affecting the stuff that you don't want to die.

So in this case, let's say, you'll apply protons of a certain energy for some point, and then another energy, and then another energy. And you can maximize the dose to a pretty flat level, while minimizing the rest of the dose to the patient. So even while changing energies, the most dose is done to the tumor, and as little as possible is done to the rest of the person.

We already talked about brachytherapy, but we didn't say why it works. This is the first major topic we'll be talking about in this course. It relies on natural radioactive decay. And for natural radioactive decay, you need to understand decay diagrams, which are energy level diagrams of which isotopes turn into which others, by which methods, and how much energy they release in each type of decay.

So for example, the common one is iridium-192, a pretty biocompatible isotope because it's, well, it's like a noble metal. And iridium-192 can decay by one of three pathways and become platinum-192, gaining a proton. Gaining a proton-- what has to happen for that to be conserved? So let's think about this.

Let's say we have platinum-192, which decays naturally into iridium-192. I can tell you, because we've drawn the diagram to the right, it's going up one atomic number. So let's just say that it had n protons, and it now has n plus 1. How do we balance this nuclear reaction? What are we missing? Yep?

AUDIENCE: [? Can the ?] [? neutron ?] [? turn into ?] a [? proton? ?]

MICHAEL SHORT: Can the neu-- OK. So there's a neutron somewhere in this nucleus that turns into a proton. What are the three-- what are the things that we have to conserve in any nuclear reaction? Yep?

AUDIENCE: Just a question. Doesn't it go from iridium to platinum, not platinum to iridium?

MICHAEL SHORT: Yes. Thank you. I got that backwards. But the numbers are right. The symbols are wrong. Something else I'll mention about this class. Please do stay on your toes to correct silly things like that.

I don't do scripts because you didn't come here to see me read off a piece of paper. Everything's live. All the derivations are going to be live because its more interesting. It's certainly more interesting for me to teach, so thank you for catching that. And please do stay on your toes if you something silly, especially if it's just not the same as on the screen.

So like Luke said, we made a proton, or a neutron turned into a proton. What's not conserved in this reaction? Yep?

AUDIENCE: Charge.

MICHAEL SHORT: Charge. How do we balance that? Well, let's add some other particles. There's got to be some sort of radioactive decay. So what are our choices of particles? Yep?

AUDIENCE: An electron.

MICHAEL SHORT: Sure. An electron. Or more specifically, we'll call it a beta particle. Just like a gamma ray is a photon that originates in the nucleus, a beta particle is an electron that originates in a nucleus. You can't tell it's a beta particle just by looking at it. An electron is an electron. The only way you'd know is either by its energy, or by because they're another source of electrons nearby.

So in this case, we get beta decay. This looks fairly balanced. One thing that I'll put in is beta decay is accompanied by an antineutrino, but I did not expect anyone to know that. I just wanted to make sure it's up there for completeness.

So what we're relying on is the movement of these electrons, which are high charge and low mass, which means they're very low range. Which means when you implant a brachytherapy seed into a person, the irradiation volume is only as large as the energy of that beta particle will allow.

The maximum energies for these beta particles are given by the differences between the starting and the ending energy. The way these diagrams are constructed is your ending energy is usually at an energy of zero, which we refer to as the ground state of that isotope. And all of these are relative energies in MeV, or megaelectron volts.

So for example, this iridium-192 has a 40% chance of decaying by beta to platinum-192, which means the electron can have up to 1.4597 MeV. And if we know its energy, we know its maximum range. So selecting the right isotope and the right activity for the right tumor is quite important.

Notice that there's also other ways in which this thing can decay. It might release a beta particle of a lower energy and reach what's called an excited state of platinum-192, which can then decay by just giving off this extra 612 keV of energy to the ground state.

So let's write that nuclear reaction. Let's say we have platinum-192, and I'll put a star to mention that it's excited, becomes platinum-192. Where did the energy go?

AUDIENCE: Gamma ray.

MICHAEL SHORT: Gamma. So why do you say a gamma ray?

AUDIENCE: Uh, because that just seems to me like the biggest source of energy that's released in a reaction like this?

MICHAEL SHORT: So you said it's because it's the biggest source of energy that could be released?

AUDIENCE: Well, it seems to me, yeah, like, intuitively that would make sense.

MICHAEL SHORT: OK. What do you think?

AUDIENCE: Isn't it a thing when an electron loses energy or drops an energy level to release the proton?

MICHAEL SHORT: Indeed. If an electron drops down in energy levels, you'll have released an X-ray or a photon. But that's not a gamma ray. It's not coming from the nucleus. Yep?

AUDIENCE: [INAUDIBLE]. Doesn't it have to be a gamma ray because of-- like, that's the only way it can conserve mass [? momentum? ?]

MICHAEL SHORT: Exactly. So the question with this is, what do we have to conserve? Mass momentum energy charge. If we have platinum-192 go into platinum-192, the mass is pretty much the same. Yep. Question, Luke?

AUDIENCE: What does it mean to put platinum in the excited [INAUDIBLE]?

MICHAEL SHORT: It means it's at a higher energy nuclear state. It means that there is excess energy in this nucleus. So the difference between ground state or whatever of iridium-192 and the ground state of platinum-192 is 1.4597 MeV.

Notice I'm not rounding. Don't round. And we can end up with a beta particle that doesn't quite release all that energy, leaving some in the nucleus in what's called an excited state.

It's analogous to if you have, let's say, an atom of a, whatever that happens to be. And since you started talking about different electron energy levels, maybe this atom is helium. And it only has two electrons. And one of them gained some energy becoming excited up to the next energy level.

Same thing, but on the nuclear level, these excitations are not in the eV range, they're in the MeV range. But you can think of it as a precisely analogous process for the time being. There are excited nuclear energy levels, and they can also decay by photon emission-- in this case, gamma emission because the masses are basically the same.

Remember that the rest mass energies might be slightly different, but the charge is the same. There's no real change in momentum because this is a nucleus that started at rest. And this way the energy can be conserved. Yeah, Sean?

AUDIENCE: [INAUDIBLE] in different cases, if they're excited, can they just go through another decay process?

MICHAEL SHORT: Absolutely. So there are multiple isomeric transitions or gamma rays. So let's chart one of the paths through here. There's a 14% chance that iridium decays to this excited state, and it can then decay by gamma ray to another excited state, and then decay to ground.

So there are lots of different possible pathways. I've chosen a particularly simple isotope because it fits on the slide. In your homework, you're going to get to look at the decay diagram for plutonium-239.

There are not enough pixels in this projector to show the full complexity of that. So you'll have to zoom in a little bit. But I'm not going to ask you to do anything with it except for look at the three most likely transitions out of dozens, maybe scores, who knows? You guys will see.

So that's a good question. Yeah. It can decay from an excited state, to an excited state, to an excited state, to an excited state, to an excited state, to an excited state and so on, until it reaches the ground state.

AUDIENCE: But does it lose its energy, like, not by going to ground state, but by decaying in some more fission products?

MICHAEL SHORT: It wouldn't be fission products, but everything else you said is, yes, it can continue to lose energy by continuously undergoing radioactive decay. And we're going to go some of this when we explore the early origins of the universe to say, if you just started off with a soup of protons and other things, you'd start to form all the isotopes possible, and the shortest half-life ones would then decay-- successive decays, maybe multiple gammas or multiple betas or multiple alphas at the same time-- I'm sorry-- in sequence, until it reached something that was stable, or stable enough that it's still around now.

For example, there's no stable isotope of uranium. There's no isotope of uranium that will not undergo alpha or spontaneous fission. It's just that the half-life is so long, that there's still some left since the universe began. There's still a fair bit left.

But you guys are going to actually calculate as part of your homework later in the course, how much uranium-235 was there when the earth was born? And how much has just disappeared because of the passage of time?

So right now, it's typically about 0.7% U-235 by isotopic composition. It was not the case when the earth was born. But you guys will be able to figure that out. Yeah, so good question. And have a rant from me, I guess, in response. I'll try and keep my answers a little shorter.

Oh, here's a crazy one-- not particularly crazy, though. So this is molybdenum 99 decaying to technetium-99 metastable. There's lots of possible decays, but the most likely one is right here. The state above the ground state at about 140 keV, a fairly low-energy and therefore more easy to detect photon.

So if you notice, almost all the other excited states, with a couple exceptions, decay down to this 0.14 MeV excited state, at which point you get decays to the ground state. Those also have a rather long half-life. It's a few days.

So you can make moly-99 in a reactor, transport it to a hospital, feed it to someone, and use these 140 keV gamma rays, because they come from the nucleus, to image whatever the technetium will bond to. Yep, Carson?

AUDIENCE: [INAUDIBLE]?

MICHAEL SHORT: The M stands for metastable. Now, where do you see it? This one. Yep. Because the direct decay-- you don't-- you never go from molybdenum-99 to technetium-99 at the ground state. The M stands for metastable, so it's an excited state. And metastable tells you that it's got a pretty long half-life.

All of these other states are excited states. Metastable means it's kind of, sort of, stable on, like, a human time scale of things. It's not technically stable, because stable would mean infinite half-life or close enough. But metastable means long enough to be detected or used, or significantly longer than the others. Any other questions before I move on? Cool.

So you can use these to image where something is in the body. For example, you can use this to highlight certain organs, highlight anything that will absorb technetium. Or if you attach, let's say, the technetium to a type of sugar or something else that will be uptaken by the body, you can see where it goes. And you can use gamma ray imagers to make kind of heat maps or radiation maps of where the technetium's going to find what could be causing the problem.

The problem is-- well, our main problem is there are huge moly-99 shortages. Right now the only economically viable way to make molybdenum-99 is in reactors. And there's only a few of these places in the world that actually make them. And I don't see any on the US. We get ours from Canada. And these are slowly getting closed down as we go.

So the question is, with millions of these diagnostic procedures per year, where is the moly-99 going to come from? That might be where some of you guys come in. If you can use the knowledge from this course to figure out an energetically and economically feasible way to make more moly-99, you're rich. That's, you know, life goal achieved.

Space applications-- if we ever want to get off this earth for a significant amount of time, we have to deal with the fact that there's no atmosphere in space to shield us from the high-energy protons and other cosmic rays that would otherwise, well, destroy life.

So there's a lot of interesting ideas, and a lot of problems with astronaut shielding. One of them is that the protons are so heavy-- I'm sorry-- the protons are so energetic that they're difficult to shield just by mass attenuation.

And the trick here is, well, different radiation has different penetrating power. It depends on its energy, but it also depends a lot on its charge. For example, alpha particles can be stopped by a sheet of paper. These are the MeV level helium nuclei.

Like, if you hold an alpha particle source in your hand, the dead skin on your hand stops the alphas from getting in. Remember that, because I'm going to be asking you a question later on to see who your friends are and who they aren't. I don't know if anyone knows what I'm talking about. But if you do, don't give it away.

Beta particles or electrons have low mass and half the charge of an alpha particle. They can be able to get through paper, even through a little bit of plastic. But a small bit of metal can stop them. Gamma rays go right through.

And notice that they've been drawn not quite being stopped by the concrete, which is a great shielding material. Because like I said before, you can exponentially attenuate gamma rays. You can't with all certainty stop every single one.

So then how do you stop these high-energy charged particles if the more energetic they are, the more range they are? Boost your electromagnetic field. So it's actually been proposed to have spaceships with enormous magnetic fields or electromagnetic fields around them to deflect the protons away or around the ship.

Because if you can't stop it by putting matter in the way, rely on the fact that they're charged particles, and will curve around whatever has got a high electric field around it. So this is one way of, let's say, shielding deep space missions. If you can't put more stuff in there because stuff is heavy, and launching stuff into space is expensive, rely on electromagnetism.

And there are also RTGs, or Radio Thermal Generators, or Radio Isotope Thermoelectric Generators, which are little balls of things like plutonium or strontium that give off so many alpha particles. And the alpha particles have very low range. They deposit their kinetic energy as heat in the material, and cause them to glow on their own.

If you produce enough heat, if something's glowing red, you can use thermal electric generators to capture that heat and turn it directly into electricity. This is how things like Voyager and, let's see, all the other space probes with interesting names are powered.

Once you're too far from the sun for solar power to work, you need something that doesn't turn off. So you can use RTGs, which have long enough half-lives to produce significant amounts of power for a long time, but short enough half-lives so that their activity is pretty high. And they release a lot of energy as radiation. And that radiation is heavy charged particles which you can capture as heat.

So yeah, an actual little sphere of plutonium that produces 100 watts just sitting there. There is no way to turn it off. That's the end of the sentence. It's plutonium.

And finally, there's nuclear rockets. If you think about using a reactor for thrust instead of electrical energy, the design of the reactor gets very different. For example, you can start to let things get a whole lot hotter when there's no oxygen in space to oxidize things.

And your propellant maybe would be liquid hydrogen that doesn't burn, but goes through the reactor and gets accelerated, turned into a gas with a high kinetic energy, to fire out the back of the rocket nozzle and provide the thrust that you need.

And so it's nuclear rockets that would really be the only feasible way without bending space time, which I don't think we've really done yet, in order to get to very distant stars. Like that planet they just found orbiting Proxima Centauri-- four light years away. Pretty close, right? No. Not really.

And if you think about how a nuclear rocket mission would work, well, it doesn't have to have nearly as much thrust, especially if you start from orbit. Maybe use a chemical rocket to launch yourself into orbit, and then spend half your journey accelerating very, very slowly. And then turn the rocket around, spend the other half of the journey decelerating very, very slowly. So you need a long, constant but low-level thrust for these long-live nuclear missions.

I'm going to stop here because it's five minutes before the hour. We only have a few more of these things to go through. But what I will ask is you guys hang tight for the next few minutes while these guys take the cameras apart. We're going to go to my lab and see an application of nuclear which, like I said, is plasma sputter coating.

All right, everyone. So welcome to my laboratory. This is the Mesoscale Nuclear Materials group, where we make and break materials for nuclear technology, usually not in that order. But whatever. We get it done somehow.

And this is Reid Tanaka, one of my graduate students, who has actually repaired and going to show you the physical principles and operation of a sputter coater, which is nothing more than a controlled radiation damage machine. And he'll be making some interesting door prizes for you guys.

REID TANAKA: Well, as Professor Mike Short said, this is Professor Mike Short's. He calls it something else. I call it the home-- the rehabilitative home for old, orphaned equipment and old graduates. All right.

And so this is-- actually, this piece of gear here, I did a little research on it, and I think it was built about the same time as I was entering college 35 years ago. So about 1978, maybe 1980. That's how old this thing is.

And now, so Professor Short goes around, as all of us, and we scrounge and we scab and we put stuff together. And you'll see that really indeed, we do that a lot.

So this part, we put together out of a bunch of pieces of parts. If you look at it, and I'll talk [? to it ?] a little bit. But there's a procedure that we've got [? rigged ?] [? output. ?] But we don't know [INAUDIBLE], so we just sort of throw them together.

So what you're going to see is a little demonstration of what a sputter coater is. You're going to see a little [INAUDIBLE].

AUDIENCE: Could you scoot in here, so we can [? hear your mic? ?]

REID TANAKA: It's under vacuum right now, vacuum pressure. This is our vacuum [? off. ?]

AUDIENCE: Let me just-- here-- come right here so you can see.

REID TANAKA: [INAUDIBLE] Again, there is another pressure indication, but we don't actually trust that one [? too much. ?] All right, without further ado, I'm going to power it on.

We're going to [INAUDIBLE] [? center ?] [? a ?] high voltage. It's argon in here. We've got argon supplies in that bottle over there. And [INAUDIBLE] I just turn up the high voltage power supply. Turning it up--

MICHAEL SHORT: Should we get the lights, Reid?

REID TANAKA: Voltage. Yeah. We can kill the lights.

MICHAEL SHORT: I'll go get them. I'll just get them right over where you are.

REID TANAKA: And if you see through this glass jar, it's going to be a little bit of a glow. Some of you might be able to see it already.

MICHAEL SHORT: Oh, yeah. Come a little closer. From where I am, you start to see the glowing purple plasma. So that's the ionization of the argon causing it to electrostatically accelerate towards the gold target. And that's blasting off gold items that are then coating the stuff that Reid's coating that you'll see in a sec.

But this is a controlled application of ionization and radiation damage using a couple of kilovolt argon ion-- don't know if you call it a beam, but at least in argon ion plasma.

So there's a few other things to note. Remember how we talked about charged particles having a certain range in matter? Well, charged particles in, let's say, low-energy particles in the kV range do not have a very high range even in gases, which is why Reid has this vacuum pump connected. Otherwise, the argon wouldn't make it to where it has to do the damage.

So when there's too much gas in there-- shuts off. When there's not enough argon in there, there's no argon to do the damage. So we're actually exciting about two kV ions. And their range is higher than the distance they have to travel, so they actually make it where they're supposed to go.

And this is a kind of direct application of NSE, along with a fair bit of high voltage electronics. And that's pretty much all there is to it.

REID TANAKA: OK. So we have about two minutes if you want to take a closer look and just [INAUDIBLE].

MICHAEL SHORT: Yeah.

REID TANAKA: It's not going to hurt you.

MICHAEL SHORT: No. Get right in there. Do you want to see-- if you look underneath, you'll actually see that blue glowing ring. That's actually a ring of gold that's being hit by the plasma. And that's causing gold ions to fire onto the target.

REID TANAKA: You guys all took chemistry at some point, right? Well, they tell you that one of the great mysteries of the [? world ?] [? as ?] [? we ?] [? know it's ?] [? been solved-- ?] [INAUDIBLE] take something and turn it into gold. Well, you should know that only the nukes can do that. Right?

Really, you got to get away from all the electrons and all that other chemistry stuff, and only the nukes. So if you really want to turn something to gold, you got to join the nuclear department. Just so you know that. Keep that in mind.

MICHAEL SHORT: Has everyone had a chance to get a close-up look?

REID TANAKA: And I think we got about another minute or so to let it run.

MICHAEL SHORT: OK. Anyone have any questions about what you're seeing here?

AUDIENCE: Is it getting, like, super hot in there, or--

MICHAEL SHORT: That's a good question. The temperature does not go up that much. There's certainly kinetic energy turned into thermal energy as the argon hits the gold, and the gold hits whatever you're trying to coat. But the total amount of energy, the density of that gas is extremely low.

That's another reason why in fusion reactors, the plasma is up to like millions or tens of millions of Kelvin. There's just not a lot of it. So if you look at the total amount of stored thermal energy in a fusion reactor, it's quite low, even though the temperature or the relation to the average kinetic energy of the molecules is extremely high. So yeah. Good question.

If you want, put your hand up inside of the chamber. Is it warm?

AUDIENCE: [INAUDIBLE]

AUDIENCE: It's not warm at all.

MICHAEL SHORT: Not at all. Yep.

AUDIENCE: The plasma is the argon? And where's the gold coming from? From in that [? ring ?]

MICHAEL SHORT: There we go.

REID TANAKA: [INAUDIBLE] we'll show you.

MICHAEL SHORT: Yeah. We'll open it up and show you. So I'll get the lights on now.

REID TANAKA: OK. [INAUDIBLE].

AUDIENCE: Why isn't the pressure [INAUDIBLE]?

REID TANAKA: What's that?

AUDIENCE: The pressure changed. [INAUDIBLE].

REID TANAKA: Yeah. From the point that we-- when you walked in and saw that?

AUDIENCE: Yeah.

REID TANAKA: OK. The first thing-- so this had a sort of a static amount of argon in it. And when I turned on the voltage, the high voltage, that's to create the plasma. But then it has to get fed.

And so what I ended up doing with this little knob here, I probably should explain that, is I was feeding it argon. That argon bottle from over here it's going into this chamber. When you're feeding the argon in, then the pressure came up.

And if the pressure comes up too high on this particular instrument, then it has an automatic cut-off [? when ?] the high voltage [? cuts out. ?] Because otherwise, you know, one of the reasons why it works is because we have so few atoms in there. [INAUDIBLE].

AUDIENCE: [? Good. ?]

REID TANAKA: [INAUDIBLE] what atmospheric pressure is in [? total? ?]

AUDIENCE: 760.

REID TANAKA: 760. [INAUDIBLE]. Maybe we [? actually ?] have a little bit of a [INAUDIBLE]. So this is that-- that's the gold ring.

AUDIENCE: [? Neat. ?]

REID TANAKA: And in the chamber--

MICHAEL SHORT: You can put the-- you can put the ring facing down for stability if you want.

REID TANAKA: What's that?

MICHAEL SHORT: I said, you can just put the ring lying flat down if you want for stability. Yeah.

REID TANAKA: And in the chamber-- the purpose of having this, actually, this machine, the main reason that we use this for is if you have something that you want to put into a scanning electron microscope, and--

MICHAEL SHORT: We're actually going to use one of those in class, so-- yeah.

REID TANAKA: You need to have some kind of conductive coating on it. So if you're looking at-- [? especially ?] like [? biologic ?] [? stuff, ?] you actually coat it with something that's conductive.

So there you see, it has a gold coat of about, I would guess, I think for as long as we did it for, something on the level of 200 [INAUDIBLE]. It's a pretty thin coat.

MICHAEL SHORT: That's all you need, though.

REID TANAKA: Right.

MICHAEL SHORT: Remember, after quiz number one, we will be piloting-- well, two of you guys we'll be piloting a scanning electron microscope down in the basement. And before we look at whatever samples you want to see, whether it's one of your eyelashes, dust on the floor, or a bug you found or something, we'll want to coat in gold, so that the electrons that we use for imaging will have a place to go. We'll have a conductive path, and they won't charge up, ruining the image.

REID TANAKA: All right. I have a question.

MICHAEL SHORT: Yeah?

REID TANAKA: Is anybody-- was anybody here born this Millennium? Anyone? 2000 or later? Nobody. Anyone in 1999? Nobody in 1999? [INAUDIBLE]. How about '98? You were born in '98?

MICHAEL SHORT: There we go.

REID TANAKA: All right. That would be-- [INAUDIBLE] brought my glasses. I've got that 1998 dime here. It's now gold-coated. And you can have it. [INAUDIBLE] [? too ?] [? bad. If ?] [? somebody ?] [? wanted ?] [INAUDIBLE] you got a quarter. You [? could lie ?] [? and ?] [? say-- ?] But I guess you are the youngest [INAUDIBLE]. Yeah. All right. So you win this. Now, it'll rub off.

AUDIENCE: OK.

REID TANAKA: So [INAUDIBLE] you--

AUDIENCE: [? I'll ?] [? probably ?] keep it in a plastic bag.

REID TANAKA: And--

MICHAEL SHORT: [? Gold ?] [? change. ?]

REID TANAKA: I guess the other ones go to people that [INAUDIBLE]. Oh, no '97. How about a '96? You're a '96? [INAUDIBLE]

AUDIENCE: [? There's ?] [? three. ?]

REID TANAKA: What's that?

AUDIENCE: There's three '96s,

REID TANAKA: Oh, there's three '96s? OK. You get the-- you get the [INAUDIBLE].

AUDIENCE: [INAUDIBLE] over a year old.

REID TANAKA: All right. Who wants the nickel that's a '96?

AUDIENCE: [INAUDIBLE].

REID TANAKA: You going to arm wrestle for it?

MICHAEL SHORT: There you go. Right in front of you, Reid.

REID TANAKA: Well, there's three of them. OK.

MICHAEL SHORT: OK.

REID TANAKA: [INAUDIBLE].

AUDIENCE: Thank you.

REID TANAKA: And who are the other two '96s? You're going to have to arm wrestle. One gets a quarter, but one gets the dime.

MICHAEL SHORT: [INAUDIBLE]. Yep.

REID TANAKA: That's the only fair way of doing [? it, I think. ?]

MICHAEL SHORT: That's not a nuclear thing, but if it's fun.

REID TANAKA: [INAUDIBLE]. Here you go [INAUDIBLE].

AUDIENCE: [INAUDIBLE].

REID TANAKA: And there is the quarter [INAUDIBLE].

AUDIENCE: Thanks.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: This one?

AUDIENCE: [INAUDIBLE].

AUDIENCE: Yes. [? Because ?] [? it ?] [? was ?] [INAUDIBLE].

MICHAEL SHORT: [INAUDIBLE] actually [INAUDIBLE]. It's just--

AUDIENCE: It's [? memorable ?] [INAUDIBLE].

REID TANAKA: OK. Yeah?

AUDIENCE: So is that gold deposited anywhere else in that chamber?

REID TANAKA: Yeah. If you look-- actually, if you look in the chamber, I mean, this is all- this is all [? from it ?] [? being ?] [? sputtered. ?] And if you look around-- I can turn this a little. Look at the glass. It gets on the glass, too.

So it actually gets-- it gets everywhere. But it's mostly directed to that area that you saw [INAUDIBLE]. I have another offer. Are you guys all nukes? You guys are all going to be in the department?

MICHAEL SHORT: All but one.

REID TANAKA: Ah.

AUDIENCE: [? Not me. ?]

MICHAEL SHORT: But we have a nuke enthusiast. So-- otherwise, wouldn't be in this class. And anyone scared of nuclear is probably not in this class.

REID TANAKA: So obviously, it was pretty easy for us to do. We have this machine here. If you're going to be part of our department, if you want to just come in, we can make you a-- we can make you a quarter, OK? I mean, I could even supply them. I feel rich [? enough ?] I can [INAUDIBLE], because all this grad student-- graduate school money I'm getting.

MICHAEL SHORT: Nice.

REID TANAKA: But-- anything else?

MICHAEL SHORT: Any questions for Reid on what you just saw? The goal is to sort of give you a real life, you know, learn 22.01, you'll understand how these things work, and how you can modify them, create new stuff. That's the general idea.

Same thing behind looking at the electron microscope for the focused ion beam, EDX elemental analysis. I want to bring what we're teaching you to life as often as we can. Since we only got one recitation a week, we'll be doing it about that much.

Once in a while I may schedule some extra stuff as long as folks are available. But we're going to try all we can to have days like this, where you get to see what you're learning in real life.

AUDIENCE: It was called a sputter?

REID TANAKA: Sputter coater.

AUDIENCE: Sputter coater.

REID TANAKA: Sputter coater.

MICHAEL SHORT: It's because the process of the argon hitting the gold is actually known as sputtering, which is the blasting off of surface atoms by energetic particles. It's a controlled form of radiation damage.

AUDIENCE: What's that Swagelok?

MICHAEL SHORT: Swagelok.

AUDIENCE: Swagelok.

REID TANAKA: Yeah.

AUDIENCE: So what's a Swagelok?

REID TANAKA: Well--

MICHAEL SHORT: Do we have any pieces here? Let's see.

REID TANAKA: [? We ?] [? have ?] [? lots. ?] [INAUDIBLE] if you go back [? around ?] [INAUDIBLE] tubing that you see back in there. They're connected so they don't [INAUDIBLE]. [INAUDIBLE] [? piping ?] [INAUDIBLE]. It's proprietary--

MICHAEL SHORT: They're all in use.

REID TANAKA: --made by the Swagelok companies to [INAUDIBLE].

MICHAEL SHORT: Oh, here we go.

REID TANAKA: So I don't know if Mike's going to take you around.

AUDIENCE: [? Absolutely ?] [INAUDIBLE].

MICHAEL SHORT: This is Swagelok tubing. It's got a two piece ferrule, which [INAUDIBLE] a metal-to-metal seal for moving liquid or gas. And it takes an insanely high pressure.

So actually, over in the next room, we can look on our way out, we've built a reactor simulator, like an experimental reactor that replicates all the conditions except for the radiation. We had to make it entirely out of Swagelok tubing, because this stuff can hold the pressure and the temperature without deforming too much. So when you want to make it absolutely airtight seal, use things-- Swagelok or things like it.

AUDIENCE: Is it stainless steel?

MICHAEL SHORT: This is stainless steel. Yep. But they make it out of titanium or other things, too. But stainless steel works for us.

AUDIENCE: That's cool.

AUDIENCE: In a PWR, how much pressure is there?

MICHAEL SHORT: In a PWR, there's 150 atmospheres of pressure. It's also 150 atmospheres of pressure over in the room next door.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Like I said, it's all the same conditions as a reactor except the radiation. The pressure is what makes it really dangerous.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Yeah. We'll look through one of the few bulletproof glass shields. Because if anything blows on that loop, it's like a proj-- it is a projectile. We've only had one explosion. There was no temperature at the time, but it sounded like a shotgun blast over the side of your shoulder. It was loud.

AUDIENCE: You in the room?

MICHAEL SHORT: The loop was right here, and we were right in front of it. Then the loop jumped up maybe an inch. And we jumped up about three feet. We got scared. That was what happens when you improperly torque a high-pressure fitting. Because you've actually got to tighten these nuts down to not too low and not too high of a torque, otherwise, they don't seal.

And usually, you only find out that they don't seal when they're approaching close to their rated thing. And you're like, great. It's at half pressure. It's OK. You reach 99% pressure and kaboom. That's what happened.

Cool. Thanks a lot, Reid, for showing this to us and taking time out of your day.

REID TANAKA: No problem. Anytime.

MICHAEL SHORT: I hope you guys enjoyed it. So no problems to work through this week. That's going to change starting Tuesday, next class. So have a good weekend. And I'll see you guys all on Tuesday in Room 24-115, next to the room where we were just in.