[SQUEAKING]

[RUSTLING]

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PROFESSOR: Today I just want to review some radiation basics. Now, it used to be that there was a big pset on calculating the number of people who die from a nuclear accident but I have, this semester, taken out the psets. And so what we will do is we will do this calculation in class next Wednesday as a whole class.

And this lecture was previously to prepare you to do the pset because there's a mix of backgrounds. I think I'm still going to give it. And for a lot of you, this will be a lot of review. There might be some new information. And that's great. And maybe you learned something, and maybe you know it all.

All right, so let's just have a quick review. Just to first remind you, there's something called non-ionizing radiation versus ionizing radiation. Non-ionizing is stuff like radio waves and microwaves and so on, visible light. And when you get towards the ultraviolet, the energies of the photons becomes energetic enough that you can actually liberate electrons from atoms. And that is what makes it ionizing, and that's when you start to get radiation effects that break down DNA and cause cancer.

So photons are where we normally start thinking, but there's also charged particles. There's a lot of different ones. You have alpha particles, which are basically a helium-4 nucleus, protons. Muons we don't think of very much, but they show up in cosmic rays. And beta particles, which are just basically-- beta plus and beta minus, either free electrons or free positrons, positrons being the antimatter analog of an electron.

And you say, well, where in the world is that going to come from? And actually you do get it in these reactions. It does show up. These positrons, antimatter does show up in these reactions.

So these things are being charged, have an electric field associated with them. And as they move through matter, those electric fields interact with the electric fields of the atoms, of the electrons. And that allows them to interact in a variety of ways, typically off the electron structure, but sometimes off the nucleus itself.

And then you have charged neutral particles, namely the neutron, which is, of course, only going to interact through the strong force and thus will only interact with the nucleus of the atom. But when those interactions do happen and they're not very-- these particles, they fly through matter, and they're interacting instantaneously.

And they're slowing down and depositing energy in just the thinnest layers of matter. But these things can penetrate quite deeply because they're not charged. But when they interact, they're very dramatic.

All right. So you've probably all seen this from high school. Heavy charged particles get stopped by things like paper. Lighter, thinner smaller ones can go into your hand. But they'll be stopped by something that has a high density of electrons, so like metal, which has a sea of electrons.

Neutrons are absorbed in water because they scatter off of like hydrogen. And gamma radiation can easily penetrate all these things. And you need wind up basically needing lead as a shield.

It's a very simplified view. In reality, this is what it looks like. You have just crazy number of reactions occurring with matter of all kinds. Let's just talk about these a little bit more.

So the three principal reactions that dominate are the photoelectric effect, the Compton effect, and pair production. And all of these depend on the energy of the incoming particle and on the z, or the atomic number of the nucleus.

So the first process there on the top left is photoelectric effect, and this is usually a dominant process when you have a low-energy photon. So the photon is usually below a few hundred keV in energy. And what it does is it transfers all of its energy to an electron and kicks out the electron, usually from an inner shell.

And so now you have this high-energy electron, which is traveling, which is also charged. And that's going to transfer further energy and so on. So this is what I think Einstein received his Nobel Prize for.

The probability of this increases dramatically with atomic number, basically somewhere between z cubed and z to the fifth. And it decreases dramatically with the energy of the photon, about 1 over E to the-- or E to the minus, dependence on E being energy, obviously.

The Compton effect is the most common effect. So in the Compton effect, you have a photon coming in. It looks like it's going to be photoelectric, but actually what it does is it scatters off of this so-called quasi-free electron. And it just gives up some of the energy to the electron and kicks out the electron. And then a lower energy photon continues, so you get this branching.

And this is something that basically leads to these kinds of showers. You see these branching events in matter because of this. So essentially the Compton cross-section is essentially proportional to the number of atoms-- sorry, the number of electrons in an atom. So it basically just scales with the atomic number.

If you have a very high-energy photon, it can interact with the coulombic field of the nucleus and split into an electron and a positron. So it goes from being a mass-free, matter-less thing, and it creates matter. And then the positron will touch something else and then annihilate and create a photon back.

And this is pair production. To do that, you have to have an incoming photon whose energy is high enough that it's higher than the rest mass of these two particles, and that is 1.022 MeV. The probability of this happening increases dramatically as the photon energy goes above 1.02 MeV. And it increases roughly as z squared. So this really is something that happens in high-z materials, gold and so on. It's not going to be a dominant process in human tissue, for example.

So these things all combine in this array. And you get basically two types of behavior. If you have energies-- if you have radiation that originates either from gamma radiation or electrons, you'll get these branching phenomenon, where you have an interaction, and then the particle travel some distance and so on. And we call this low LET, which stands for linear energy transfer. And so you'll have these events separated by hundreds of nanometers, and you get these branches.

If instead you have a particle like a muon or an alpha particle, which is heavy, it has a large field, you will get what we call high LET event, radiation interaction. So basically this is just like this has it's such a huge massive particle and it has so much field. And it's just slowly interacting, interacting, interacting and just leaves this wake of destruction.

And it doesn't go very far. But the damage it does do is very dense. And so this kind of radiation tends to lead to more localized cell damage and is more likely to kill a cell or do DNA damage.

So actually that's very useful if you're trying to treat cancers. And you can put that radiation source like that right next to the tumor. Then it's really good at not going very far into healthy tissue and also just really doing a bad job on the unhealthy tissue.

All right. So these are obviously basic, different rate of each. So radiation from the decay of nucleotides, a key thing to remember is that the activity level is equal to the rate of decay for the isotope. And that means that you can specify these things are all proportional, the activity, the number of atoms present in the isotope, and the mass of that isotope.

If someone gives you one-- they say, oh, there was a 100 becquerel-- that's a measurement of activity-- of iodine. You can calculate either of these because they're all directly proportional. Does anyone know how to-- I assume people know how to do this. I will do it for if you don't know how to do it.

But basically, you have these equations that give you the rate change, which is the activity proportional to the decay constant, times the number of atoms. The decay constant is related to the half life by this relationship. You should basically know all this. And then you can just calculate forward.

I think, unless someone has not seen this, don't be shy. All right, I will just zoom through this. All right, so we have two principal units for decay. In case you don't remember, the CGS unit is a decay per second. We call it a Becquerel. Sometimes you'll see this older unit called a Curie. And you have to remember this number, which is really annoying, 3.7 times 10 to the 10. Decays per second is a Curie. So Yes, a Curie is a lot of radiation compared to a Becquerel.

All right, so sometimes, you might think about-- so in movies, you often hear people say, oh, it has a half life of 30 years. Therefore it won't be safe to be there for 30 years. No, only half of the atoms are decaying in 30 years. How long does it take to get safe? Strictly speaking, almost never. But a nice couple orders of magnitude reduction is often practical. And so 7 half lives is kind of a good rule of thumb for when you're thinking of something being irrelevant.

So you're just thinking ahead, about contamination from fallout. And you think, oh, cesium-137, big isotope in fallout, has a half life of 30 years. How long do I have to worry about it? Something like 30 times 7, a couple hundred years, something like that.

All right, so of course, there's a lot of radiation in the environment. There's basically, in the United States, roughly-- this is the gamma dose. This is measured 1 meter above the ground, from all isotopes. It comes from-- we call this ground shine. Ground shine also includes fallout. So when we do our calculation class, we will calculate the ground shine from a nuclear accident.

But there's a naturally occurring ground shine. And this comes from, basically, three sources, uranium and its daughters, thorium and its daughters, and potassium-40. And these are the principal things. So potassium-40 tends to aggregate in places that have silica, or mica, or salt deposits, and so on. And then, you might find uranium and thorium in things like granite, and so on and so forth.

So what can I say about all these? I think I'm going to go through a level-- this is a level diagram. But let me-- I'm going to have one a little bit later. I think I want to talk about that a little bit later.

Basically, here's, just briefly, an example of potassium-40 decays into argon and calcium. Here are the uranium decay chains. You've probably seen these. The issue with these is, being a heavy isotope, it, of course, has a lot of things it can decay into. Thorium goes to-- starts out as uranium-238, becomes thorium, protactinium, protactinium, uranium, thorium, radon, radium, polonium, and so on and so forth, bismuth.

The worst of these is radon. It has the issue that it has a half life of almost four days, and it's a gas. So all this stuff is typically happening underground, in the rocks. And it's fine. But then, it produces this radon, and that seeps out. And actually, this is responsible for-- it's the biggest single source of natural radiation exposure for most Americans. And it's comparable to the average dose that an average American receives from diagnostic medical X-rays and procedures. It's a big source of dose.

And depending on where you live, and what kind of rock is under you, and how close it is to the surface, this can be a big problem. What happens is it's a gas. It floats into the air. It collects in your basement. You Inhale it. And then, it decays in your lungs. And the rest of this decay chain then happens in your lungs. And that's not a great thing.

The other thing to point out, I guess, with these is that-- this is thorium. Thorium is common. You find it a lot in different kinds of sand. It's not such a big thing for Americans unless you have a brick house or something. But it goes to show how the chemistry really matters. Actually, there's also a radon here. But this is less of a problem, this one.

The chemistry of these things affect where they are aggregated, how they are transported into different kinds of water-- into different kinds of minerals by water-- and so forth. And I think this is a good opportunity to bring up the idea of secular equilibrium. So if we just look at the half lives, at the top there, you see that the half life of thorium-232 is 10 to the 10 years, 1.4 times 10 to the 10. It's a very long time. And then, everything else is short-- five years, six hours, one year, three days, 55 seconds, tenth of a second, 10 hours, 60 minutes, 0.229 microseconds.

So what does this look like in practice? In practice, you have this reservoir of thorium. Nothing is happening. And then, if we just speed up time, one thorium atom decays, and then goes, doo, doo, doo, doo, doo, doo, doo, doo, doo, doo. And you have all these other decays. So essentially, all of these isotopes are present with the same rate as the thorium atom. That's the rate at which they show up. And you can treat all of these subsequent decays as basically happening almost simultaneously with the rate of thorium.

So this is an important factor when you're-- or an important concept when you're doing calculations of dose. Because you might have one really long-lived isotope, which is really controlling everything that's going on. And so you just want to keep this in mind, because it can ease the calculations. You would add up all of these energies and all of these decay paths, and just attribute it to that mother isotope decay time.

You can, I guess-- yes, there it is, written out. You can figure out the exact amount of every one of these given this-- think of this as a set of differential equations, where you have one bucket slowly filling into another bucket, pouring into another bucket. And you can solve that bucket for an arbitrary number of buckets. And this is called the Bateman equation. So there it is. And this will tell you the activity of any given isotope I at time t for a chain. And you would follow this-- you have to work out this equation.

But you don't have to write this down now. If you really want to know this, just remember the name "Bateman equation," and go look it up. And there is a closed form way of figuring all this out. All right? So secular equilibrium, important concept to just keep in the back of your head.

All right, so next week, when we do the calculation, we're not going to be interested in naturally occurring stuff. We're going to be interested in radiation that comes from nuclear reactors. And most of that comes from fission. Of course, when you have fission, you have two radioactive nuclear fragments. And if you remember back to your basics, this isotope is stabilized by a high number of neutrons because it's a heavy isotope. And you need those extra neutrons to hold it together, more strong force against the coulombic repulsion.

What happens is, now these fragments are smaller, there's an excess of neutrons. And so you have, principally, a mode of decay that is beta radiation, where these neutrons convert-- they pop and they convert themselves into protons. And then, the charge balance is maintained by then ejecting an electron and an antineutrino. And that is beta decay. And that's the principal mode of decay that we really see from these fission products. So instantaneously, fission is just giving off a few neutrons, which is obviously radiation. But it's actually the decay of the fission products, which happens later, that is the concern for reactors.

There are, in spent fuel, still sources of neutrons. Some of these fission products have a mode where they will eject the neutron. And also, you have neutron capture, where you have what are called transuranics. So you start with uranium-235 or 238, and it absorbs a neutron, and becomes uranium-239. You can keep absorbing neutrons, and just by luck, not get fissioned, and be in the spent fuel. And then, some of those transuranics want to decay by a neutron. So you will have a neutron source in spent nuclear fuel that you have to worry about when you're talking about dealing with spent nuclear fuel, not so much, as it turns out, dealing with reactor accidents. And that's because those heavy isotopes don't typically come out during the accident. It's really the lighter fission products.

So which fission products are there? Well, in principle, almost anything can be there. Here's the table of isotopes. And you break up that uranium, and you just wind up in two spots on the chart, where the number of protons and neutrons adds up to the number that is in u-235 minus 2 or 3 neutrons that came out during fission. And that makes everything complicated. Because you have basically every single element in there, and that makes it a pain to work with.

There is a reliable statistical distribution. Have you probably seen it? It looks like an M. I should have put a plot of it in here, that tells you which isotopes are more likely to come out. But basically, you do have to deal with everything.

All right, so let's just look at the situation in what's going on in the fuel. So because of this, all of these fission fragments, which are undergoing decay over time scales of between minutes and hundreds of years, thousands of years, we have to keep the cool-- sorry, keep the fuel cool so it doesn't heat up from the decay and melt. And so all of this, of course, happens under water.

Here's a picture of a fuel machine unloading a PWR pressure vessel. Here is a fuel bundle being inserted into the spent fuel pond. These barriers here, which make these little casks, are neutron-absorbing so that we can squeeze more fuel bundles, and they won't start reacting with each other. Most of the blue light in this photo is just blue because of Rayleigh scattering of the light. But you can see, right here, the Cherenkov radiation on this freshly unloaded fuel bundle.

So how spicy are these things? So here's a good way to understand that. This is a function of the time after discharge of a single bundle. And we have two bundles for you. The old fuel, 33 megawatt days per kilogram, that's kind of where we were in the '70s in terms of how far we would burn the fuel. Now we burn the fuel much further, so there's more radiation in it, 50 megawatt days per kilogram. So that's the solid green line.

And you can just see, immediately, you have a dose rate of something like 100, or more than 100, sieverts per hour 1 meter from the center of the fuel bundle. So it's like, if the bundle is there, and I'm standing here, I'm going to get 100 sieverts per hour. The LD50 for that is-- I will have a 50% probability of dying if I stand there for 2 minutes.

But you can see it cools down pretty fast. It's down to a factor of 10 times cooler after about 15 years. And it gets to another 10 times cooler after about 100 years. But even then, we're still talking about an LD50 in 3 to 4 hours. So if I were trying to steal this fuel bundle and manipulate it, I don't have a good chance of surviving. No matter what, I'm going to get radiation illness.

It's a big thing. And it's actually part of our protection against theft. The IAEA has this definition of self-protecting. And I think the self-protecting definition is roughly out here.

So what we don't want, of course, is to get any of this inside of our body, because that's really seriously problematic. And so we don't want any of this being dispersed. So how does this stuff get dispersed? Mostly, this happens because the field bundles get too hot, because they haven't been maintained cool in the pool, or some event happens, which melts the fuel. And that causes the isotopes, which are more volatile-- which is to say they have a lower melting and vaporization temperature-- to start boiling away. And then, they vaporize, and they travel in the air. And this can happen, for example, if have a fire, various things like that.

So the principal isotopes that we worry about in an accident are these, cesium-137, americium, cesium-134, and then these transuranics-- or americium is a transuranic-- plutonium, americium, and these other plutonium isotopes. These are the ones that really contribute a lot to nuclear accident dose. There are some other things in here as well, but they tend to be daughters of these things, bismuth and so on. Barium is another one.

So when we do our calculation next Wednesday, we're going to really focus on cesium-137 as the principal isotope. Because you can see how This is something that is high for a long time. This is a log chart. So big difference if you're a little further up on this chart. This thing tends to really dominate. So it's kind of a good first order calculation. But when you do talk about spent fuel, and you're talking about hundreds or thousands of years, then these transuranics begin to matter more. And that's what matters in the very long run.

All right, so how does this accident occur? So this is the inside of a reactor. The pressure vessel, the reactor core is over here. That's just the edge of the well. It goes like this. And the reactor is roughly there.

So the first thing that can happen is you have some kind of loss of cooling accident. And inside the core, you have some fuel that is exposed. And that fuel will then not be locally cooled. And just from the radiation decay, it will heat up, and the cladding can blister. And you can have melting of the fuel, and-- we talked about this in the last class-- something called corium, which is basically a molten fuel, dripping down to the bottom of the pressure vessel. That's your principal concern.

But we also have to worry about this thing. This is the spent fuel pool, where all the spent fuel goes. And there can be decades of fuel in here. This fuel has been cooling. This fuel is fresh and extra spicy. But there's a lot more fuel here than there is over here.

So what happens is you have this machine that pulls out the fuel, and it transfers it through this sluice gate. And then it brings it and sticks it into one of these slots, as I showed you earlier. And then it sits in this pool for some period of time, until it's cool enough. And then you put a concrete cask in here. And then you transfer the fuel into the cask, seal the cask, and you can take it out. And then once it's cool enough, it can go into this cask and just be air cooled. And then you stick it outside the reactor on a platform.

So there's about 6.5 meters of water, 20 feet of water, above this fuel. And it's there for two reasons. One is, it's a lot of mass that acts as a biological shield-- it protects the people who are in the plant-- and two, obviously, to keep that water cool.

In 1979, Sandia National Laboratory, which one of our government labs, realized that one of the scenarios for a potential reactor accident was not just what was happening over here in the core, but that you could have the water leak out of this pool somehow. And that could cause the zirconium clad on the outside of the fuel to heat up to the point where it would spontaneously ignite. It would undergo an autocatalytic reaction.

Even if there's some water, and there's steam coming up, at a certain temperature, it will rip off the oxygen molecule from the water atoms in the steam and basically have a runaway oxidation reaction, which is burning. So it will spontaneously catch on fire if it gets too hot. And then, of course, you will boil away all of these encased radionuclides. And you could have a very big problem.

That, so far, has never happened. But it is considered to be a hypothetical concern. It receives some attention. But actually, during the Fukushima accident, we had a loss of offsite power event that got us pretty close to this particular scenario happening. So let me just tell you a little bit more of what happened.

Basically, because there was no offsite power to the reactor, all the systems that regulate the water level and pump in the water to maintain the safety of this pool were disabled. And very slowly, the pool began to heat up. And you can see, in this photo, this steam coming off of the reactor pool. It's boiling the water in the pool because there's no cool water being circulated into the pool.

This photo was actually taken after TEPCO was able to deliver fresh emergency water into the pool using fire trucks. So they were able to raise the level. But you can see here-- you can see kind of see the rust line here. And so the level is still kind of like 8 to 10 inches below where it normally was. The other thing to see in this photo is you can see daylight, up here. Because the reactor building had exploded because of hydrogen. And so what happened is this radiolysis of water produces hydrogen gas. It accumulates in the building, and then it ignites. And it blew the reactor building apart.

So this spent fuel pool was just open to the outside environment, and this boiling off the water. And they were worried that the water was going to reach the point where the fuel would become uncovered. So they kept bringing in fire trucks, and shooting hoses, and hoping that-- on the top of the building, and hoping that-- it would rain into this pool to refill it. Despite all that effort, actually, they thought they were hosed, no pun intended.

So this is a chart from the National Academies that shows, basically, what happened. The official prediction of the water level was the black line. So here's the accident. They thought that the water was basically evaporating at a constant rate because of the heat. And then they realized that they need to do something about it, so they kept bringing in fire trucks. And they got really desperate, and they kept hosing in. And they thought they had gotten some water, but then there were some issues.

And once it reached this red line-- this is the height of the water. So 4 meters is the height of the fuel bundle. The water is at 6.5 meters above that. And they thought, basically, they were exposing the fuel, and things were going wrong. And they were waiting for the fire to start. That, turns out, didn't happen.

The reality is that this sluice gate here, that is supposed to seal off this chamber that contains the reactor pressure vessel, had gotten damaged in the earthquake. And as a result, water was leaking from that vessel into the reactor, cooling-- into the spent fuel pond. And that is what-- this is the actual water level. And so they were able to-- they basically got lucky because of a leak that leaked water into the spent fuel pool. You can imagine what would have happened if, in fact, the leak occurred the other way, and there was a crack somewhere in the structure of that spent fuel pool, and it was leaking out. Then it would have been a much worse situation.

So here you can see-- these are photographs from the reactor accident. You can see a bunch of broken concrete sitting on top of the fuel bundles there. Here's a top view. That's what, basically, the fuel looked like in the pool. And this is why the leak occurred. This green thing here is the fuel handling machine that reaches into the pond and moves the bundles around. So right here is where the pond is, and that's the steam coming off the pond. So we got really lucky.

You could ask, well, how bad would this have been if this had become uncovered and caught on fire? So the Nuclear Regulatory Commission did a calculation. And they said that the radiation releases would have been about 100 times higher than they were, which, if you do the math, is about 25 times worse than Chernobyl. So even though this is a reactor that has a containment and everything else, it still could have been really bad. And just, we got lucky because of the broken gate, and no cracks anywhere else in the pool.

So do not take away the idea that Chernobyl was bad because it was a bad design, and all modern reactors can't have those types of accidents. That's not the case. A really bad accident was basically just luck away.

So let's talk about how you would calculate dose if such a thing were to occur. So we talked about these units. Those are units of decay. What we want to know for dose is energy deposited per unit mass, per unit matter. And so we have these other units of a gray and a rad. The gray is the kgs unit. And in the United States, historically, we used CGS units. They're not imperial units, but it's ergs per gram, which is CGS version.

And then, you can calculate, essentially, the dose per decay. And that gives you a dose rate. So you have your decay rate. And then, you need some measure of your dose per decay. And we'll talk about how we get that in a second.

So this energy is not just random kinetic energy that is just heating things up homogeneously. This energy is being emitted in these charged particles, which interact in all those photoelectric and other phenomenon that I showed you earlier. So the simple way-- basically, it's very complex to calculate it exactly, so we have developed these simple, back of the envelope ways of doing it. And what we use is something called the relative biological effectiveness.

And so what this does is it just attributes a number that allows us to convert from actual energy deposited to effective energy deposited depending on how the radiation interacts with the matter. So the dose will be based just on the electron energy, or on the photon energy. But then, we multiply it by some effectiveness number. And we have something called equivalent dose, which has exactly the same units, because we are multiplying it by a unitless scaling factor. But it doesn't at all mean the same thing. Once we're in effective dose, this is basically a proportionality to dose from photons. That's the idea. We'll set photons at 1, and then we'll have these multiplying factors for everything other than photons. And that's what we do.

So generally, electrons are also 1, and then neutrons of different energy, 5, 10, 20. You can see how crude this is. It's very rough-- heavier ions, and so on. So once we do that, in order to prevent confusion, we change the name of the unit. We go from grays, which is literally joules per kilogram, to sieverts, which has units of joules per kilogram, but it also contains this multiplier. So if it's sieverts of neutron dose, in fact, the actual energy deposited would be a lot less.

And the equivalent one for rad is rem, which stands for rad equivalent man. And you have this conversion factor, because we're going from CGS to KGS, of, basically, 100 rem is 1 sievert, 100 rad is 1 gray. If you can never-- sometimes it's hard to remember what that is. So a stupid thing you can remember is, you should have 100 rad experiences before you're gray, 1 per year, just to help get your unit conversion in your mind.

All right, so the average annual dose that we accumulate from background is about a millisievert, excluding radon, which is a big source. This is a very crude way of doing it. It's not how you would do it if you worked in a hospital and you wanted to calculate a dose for a patient that you were going to give them for some kind of treatment. In that case, you would do something much more fancy. You would have a tissue weighting factor. You would have a dose rate weighting factor. And you would have all of these adjustments for how fast the radiation comes in, what tissue. Different tissues have different vulnerabilities, and so on.

These numbers are very poorly understood. There's a lot of subjectivity in this. And basically, this is way too fine of a process if we're just doing reactor accidents, and it's just like people being exposed in all different ways. So we typically don't actually do this for the types of problems that we're interested in.

All right, let me talk about the level diagram. All right, so who knows how to read all these things? All right, one person. Let me go through it then. So this is a level diagram for cesium. This is the atomic number. And this is the half life. A stands for annum, 30.07 years.

It decays via two paths. Both of them are beta minus, meaning it gives off an electron. Beta plus would be giving off a positron. This path produces an electron with 0.512 MeV. This path produces an electron with 1.174 MeV. The probability of it going down this path is that. Probability of it going down this path is that. So it's just a roll of the dice depending on where it goes.

If it goes down this path, it turns into barium-136, atomic number 656, half life of 2.55 minutes. If it runs up here, then 100%-- well, actually, 85.1%. I don't know what the rest is-- basically decay by-- oh, this is actually-- I'll have to go double-check what that number is. But basically, this now decays by gamma, with this energy. So this energy plus this energy equals that energy. It all winds up in the same place.

Those energies, we call them. Qs. That's the reaction energy. So let me ask you a question. Can I just say, OK, well essentially, they're all going to wind up as barium-137. So why don't I just assume that all the decays give 1.174 MeV? Can I do that? Why? One's a beta, one's an electron, and one is a photon, but they both have an RBE of 1.

I start out here. I either go straight to here, or I go, do, do. And I have two decays, two particles versus one particle. But these two particles, the levels add up. So that level plus that level is the same as this level. Can I just treat them all as having 1.174?

STUDENT: I'd have to double-check this, but the lower energy beta probably doesn't have enough to penetrate that. Maybe it does. No, that's 500 [INAUDIBLE].

R. SCOTT KEMP: Penetration is not really actually considered at all here. You still multiply. And the way you do this is-- you wouldn't say-- if it touches your skin, if it was exposed to the outside, then there could be some adjustment. But let's just say you ingest this.

STUDENT: OK.

R. SCOTT KEMP: Yeah, so penetration doesn't really matter. I'm not going to answer this. I'm going to wait for an answer. All right.

STUDENT: You can treat them as both having the 1.174.

R. SCOTT KEMP: Who agrees that we can treat them the same, we can treat everything as having 1.174? All right, who disagrees? All right, why?

STUDENT: Well, wouldn't it be different because you have gamma that's on i versus another gamma?

R. SCOTT KEMP: That's what the RBE does. It's supposed to adjust. And you see here, the photon and the electron is both assigned, essentially, unity. So you're right. Technically, it's not exactly the same, but it's almost the same, yeah. Yeah?

STUDENT: Are we assuming, now, that that 85% is 100%.

R. SCOTT KEMP: Yeah, assume that's 100%, yeah. Just probably different levels, yeah. Antineutrinos-- so this level change is 1.174. But remember, beta minus decay includes an electron and an antineutrino. The antineutrino basically doesn't interact with matter. And roughly-- we could derive it, but I'm not going to. Roughly 1/3 of the energy is in the beta minus particle.

So if you were going to do this calculation, you would do. 0.054 times 1/3 times 1.17 MeV plus 0.512 times 1/3 plus 0.946 times 1 point-- like that. You would multiply the electron decays by 1/3, and 100% for the photon decays. Because the antineutrino is taking away approximately 2/3 of the energy. So in fact, this decay is a lot less damaging than this decay path. And the barium-137m is your enemy.

All right, so don't forget. You can estimate the beta energy exactly if you want to, using Fermi theory. But I assume that this is annoying. So just use this. This is good enough, 1/3.

All right, so cesium-137 is a very big problem. Another one that we have to worry about is iodine. Iodine is not typically produced in large quantities directly from fission products, but it is a decay product of things that are. And the reason we worry about iodine is because when we ingest it, it accumulates in our thyroid.

So it typically comes from either indium or tin, and there are these decay paths. Indium has a low melting temperature, but a very high boiling point. So it will tend to melt, but not vaporize if there's a fire. The same is true for tin. And does anyone remember what Sb is? What? Antimony-- wow, that's great.

Yeah, tin and antimony, both are unlikely to vaporize. But iodine and tellurium-- but iodine vaporizes at about 184 C, which is like your kitchen oven temperature. So this stuff all comes boiling out of the reactor. Even after the accident is over, the fuel is easily still this hot. And so this is how-- then it gets released into the environment. And you have eight days, 20 hours, and 6.5-hour half lives.

The eight-day stuff is the stuff that's really problematic. Because eight days is long enough for a plume to go into the air, to travel through the atmosphere, and to slowly settle. And what happens is once it vaporizes, it cools, but then it forms aerosols. And then they have a very slow settling based on what-- you've heard it called the Stokes settling velocity. So you can calculate, depending on the particle size, how fast these things will fall to the ground. And eventually, they'll land on something.

You'll either inhale them, or they'll land on something you eat. And because this thing stays around eight days, there's a good chance, in the immediate aftermath, that you might ingest some of this iodine. And that becomes a problem. Because then it decays inside you. Once it decays, it typically decays to xenon. The long-lived xenon isotopes actually are less problematic, because they're noble gases, and you have a high chance of them escaping from your body. But some of these shorter-lived xenons, whether that atom will escape within 15 minutes, probably unlikely.

So this is the other source of-- big source of dose after cesium. This is really only something we worry about in the immediate aftermath of an accident. We don't worry about it when we do long-term. So we will do an adjustment next Wednesday, for iodine. But most of the calculation we're going to focus on is cesium.

That's basically all I have in the review. Since we have a little bit of time, I will just show you a couple of things. So here, if we go back to remembering low-LET radiation, which is like photons and electrons, you're going to have this kind of behavior, where you have some kind of interaction, and then the particle can travel some distance before it reaches another interaction. That distance is large compared to the size of your DNA strands, which are wrapped onto these things called histones. And so the DNA is coiled into this coil of coils.

But the high-LET, like alpha particles, they're just interacting all over the place. And so you have a high probability of getting what are called double-strand breaks, which I'll talk a little bit more about next class, where you basically-- a single-strand break is where you have-- there's your DNA. And you have all these bases. So this is your sugar backbone. So typically, what will happen is you'll have some reaction come in, and it'll interact with an atom here. And it will lyse that. And then, your body has a process to repair that.

But if you have high-LET radiation, it's interacting, interacting, interacting, interacting, interacting, interacting. And so you can get cuts in multiple places. And then you can get a bigger, more dramatic separation of the DNA. And that typically results in a bigger problem.

The problems don't arise from the cutting of the DNA themselves. The problems arise from the DNA repair. And that's a really, really, really important thing to know. It's, in fact, the misrepair of DNA that leads to mutations, aberrations, genomic instability, and cell death. So we'll talk a little bit about this in the next class.

The fact that your body heals itself does not fix the problem, it is the problem. Otherwise, if you just slice the genome, and the DNA did not repair itself, the cell dies, and that's it. It either just dies, or becomes senescent and doesn't replicate. It's only when the DNA repairs itself, basically, that it's an issue.

All right, I'm going to stop there because I won't have content for the next class. But we will pick up on this talk about dose response models, how to estimate the probability of cancer given some dose in the next class.