MICHAEL SHORT: Today I want us to go more in-depth into the photon interactions with matter, and we're going to bring the theory back to something that we can actually start to use in doing shielding calculations. If you want to find out how much of this material do I need to shield this much gammas, we're going to answer that question today.

First I want to start off, again, with Compton scattering because I messed up a couple of the energy things from last time. I got excited due to an energetic coincidence between the photo peak and the continent of our banana spectrum and one of the examples in the book. So I'm going to correct that now, and we'll go through in more mathematical detail why that wasn't the case, and what the actual quirk of physics is because there is a constant energy thing here that I want to highlight to you guys.

So skipping ahead on the photoelectric effect, which I think was similar, to review Compton scattering. It's the same thing that we saw between two particles, except now one of them is a photon. And like I said, on the next homework, after quiz one, you guys will be doing the balance between energy and momentum, because the photons don't really have mass, in order to figure out what's the relationship between the incoming energy of the photon, the outgoing energy of the photon, and the recoil energy of the electron.

And so these are the relationships we were showing last time. It is an interesting quirk of physics that the wavelength shift itself does not depend on the energy of the photon coming in. As you can see, it just depends on the angle that it scatters at and a bunch of constants, where that m right there stands for mass of the electron. Now that wavelength shift-- while that wavelength shift does not depend on the energy of the incoming photon-- the recoil energy does. You can see it depends on both the energy and the angle. And the incoming energy of the photon equals h nu.

And to give that quick primer on photon things, I want to show you guys here why that's the case. So even if you have a constant wavelength shift that might give you a non-constant energy shift. So even though in this constant scattering formula, the wavelength shift only matters with the angle, the energy shift actually depends on the angle and the incoming energy of the photon.

So now let's look at a couple of limiting cases. So as we have e of the photon equals h nu goes to 0, what does t approach? The recoil energy of the electron. Let's just do out the formula. This recoil energy equals h nu, which is the energy of the incoming gamma times 1 minus cosine theta over mc squared over h nu plus 1 minus cosine theta. As h nu approaches 0, what happens here?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Yeah. H nu goes to 0. This fraction goes to infinity. And this goes to 0. Hopefully that's an intuitive explanation. If the incoming photon has 0 energy, it can transfer 0 energy to the electron. Now the more interesting case. What happens now as e gamma approaches infinity, as the photon gets higher and higher in energy?

AUDIENCE: T just approaches h nu.

MICHAEL SHORT: T approaches almost h nu. I actually want to do a quick calculation without doing all the limit math. Let's say we had energy of the gamma was 1 GeV, an extremely high energy. So all we'd plug in-- and let's say we wanted to find out what's the maximum energy of this recoil electron. And this is something I want to ask you guys. I can't remember. Yesterday did we say that t is a maximum at theta equals pi or pi over 2? What did we say yesterday?

AUDIENCE: Pi over 2.

MICHAEL SHORT: Interesting. It's pi, actually. The case where you have the largest energy transfer-- and sorry for not catching that-- is just like in a nuclear collision, if the photon were to back scatter, it transfers the maximum energy to the electron. So the analogy here is, like, perfect. Between two particles hitting and between a photon and a particle hitting, the maximum energy is when theta equals pi. And let's actually plug that in to find out why.

If we say t max equals h nu-- depends on the electron coming in-- 1 minus cosine theta over mc squared over h nu plus 1 minus cosine theta. At theta equals pi, cosine theta goes to minus 1, and so then that also goes to minus 1. And so this becomes 2h nu over mc squared over h nu plus 2. And so that without worrying about the numerator, especially in the limit of very high energy photons, you can see that that actually maximizes the recoil energy of the electron.

The reason we're harping so much on this recoil energy of the electron is because that's what we measure. So when we look at our banana spectrum, you're not measuring the energy of the photon. You're measuring the recoil energy of the electron and the ionization cascade that happens as all those electrons smash into each other, creating electron whole pairs, which are counted as current.

If you guys remember from last class-- in fact, I'll just bring up the blackboard image because we can do that. So I took a picture of the board yesterday, photon interactions Part 1. There it is. We'll just use the screen as a bigger blackboard for now. So if you guys remember, let's say a gamma ray comes in and causes a Compton scatter event or a photoelectric emission, or whatever. It doesn't matter which process.

And it liberates an electron, either by scattering off of it or just getting absorbed and ejecting it. Or it doesn't really matter how, but it creates this electron hole pair. That electron right here has this recoil energy, which depends on theta, the angle that it scatters and the incoming. Energy and that electron's going to keep moving in this material, knocking into other electrons very, very efficiently so that most of the energy of that electron recoil actually gets counted as other electrons being freed.

We're going to go over on-- well, next Friday-- electron nuclear interactions, including what's the probability in energy transfer when electrons slam into each other or when ions slam into electrons or each other? So let me go back to the slides. And so this maximum, as this approaches infinity, this actually approaches a value of h nu minus .255 MeV

Just to do the quick calculation to give a numerical example, if I plug in theta equals pi and h mu equals 1 gig electron volt, or 1,000 MeV. And can anyone remind me what is mass of the electron c squared? What's the rest mass of the electron? Sorry?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Right. While I'm usually against memorizing anything-- because that's what books and the internet are for-- this is one of those quantities that I want on the tip of your tongue as nuclear engineers. You should remember what the rest mass of the electron is because a lot of our quantities are calculated based upon it.

For example, this ratio-- what was it, h nu over MeC squared-- gives you the energy the photon in terms of the number of electron rest masses, which is a useful quantity in itself. So why don't I plug all this stuff in. So we have .511 over 1,000 plus 2 flipped over the x-axis times 2 times h nu. And we get-- so that t becomes 999.745 MeV.

Interestingly enough, 1,000 MeV, our ingoing photon, minus that equals that right there. So that's the interesting quirk of physics is as the photon increases in energy, the maximum amount of energy that it can leave with-- or sorry, the minimum amount of energy the photon can leave with, or the maximum amount it can impart to an electron approaches .255 MeV or the photon energy minus that. What do you guys notice about that number?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: That's right. It's exactly half the rest mass of the electron. So as your photons hit the GeV range and above, they can all leave with half the rest mass of the electron of energy, which means you have more and more energy able to be transferred in a given Compton scatter as the photon gets higher and higher in energy.

So for the limit of low energy, the photons basically bounce off without transferring much energy at all. And the higher in energy the photon gets, the higher percentage of that maximum transfer can be. So that's what I wanted to clarify from last time. It was an interesting coincidence that our photo peak and our Compton edge were pretty close to that number apart. But one MeV isn't quite infinity. But it is pretty close. That difference right there, what does that come out to? Before I say something stupid, I'll just calculate it.

1.241. It's like 0.218 MeV, so we're already most of the way there. So once you reach, like, 10 or 100 MeV, you're pretty much at that limit. And so what that tells you is that the distance between a photo peak and its corresponding Compton edge for high energy photons is going to be half the rest mass of the electron. Once you get to lower and lower energies, that distance will start to shrink. I'm sorry, other way around. That distance will start to grow.

And I have a few examples I want to show you. But first, in order to understand these, now I want to get into the part I told you we'd get to yesterday, which is what's the probability that a Compton scatter happens at a certain angle? And this polar plot explains it pretty well. In the limit of really low photons, like .01 MeV or 10 keV photons, you can see that this forward scattering to an angle of 0, or back scattering to an angle of 180-- there's a 180 that's blocked by an axis right there-- they're almost the same.

So forward and back scattering, there's not really that much of a big difference in probability. So if we were going to start graphing theta of this Compton scatter as a function of the-- going to introduce this new quantity, this angularly dependent cross-section. Before we were giving you cross- sections in the form of just sigmas, like sigma Compton. Now we're actually telling you what's the probability of that interaction happening in this certain angle?

So it's called the differential cross-section, and you can have all sorts of differential cross-sections, like energy differential cross-sections, angle differential cross-sections, whatever have you. So if we try and graph what dpes the shape of this look like, this polar plot on a more understandable graph, we can see that the probability is pretty high.

Let's just call that a relative probability of 1. And as we trace around this circle, that value gets lower and lower until we hit 90 degrees, or pi over 2, at which point it starts to pop back up almost to its original value. So this was for a 10 keV photon.

Now let's take a different extreme example. We have a 3 MeV photon right here. And it's that long dashed curve, so that one here in the center. So we can see that the relative probability of 0 degrees is the same. And if we trace around to 180, we're almost at the origin, which tells us that, for 3 MeV, it starts off the same and quickly drops really far down. What that means is that what's called forward scattering is preferred.

So up on this board, we were talking about what's the maximum energy that a photon can transfer, which is always in the back scattering case. The other part to note is that that back scattering probability gets lower and lower as the photon gets higher and higher in energy. Yeah.

AUDIENCE: So it's that basically saying, since we said forward scattering [INAUDIBLE] as the energy gets higher, you just have a harder chance of it interacting.

MICHAEL SHORT: Exactly. Yeah. The cross-section value, well, yeah, it goes down as you increase in energy. So a total forward scatter, if you had a true forward scatter where theta equals 0, I'll call that a miss. It means that, because we saw on this formula up here when theta equals 0, there is no energy transfer. Nothing. And so yeah, that would be to me like a miss. If that angles ever so slightly above 0, then there is some scattering, but there's very little energy transfer. But that smaller energy transfer becomes more likely when the photon goes higher in energy.

These are these sorts of cause and effect relationships I want you guys to be able to reason out. If I were to give you a polar plot of this differential cross-section with angle and energy, I'd want you to be able to reproduce this and tell me what's really going on. If we fill in one of the ones in between-- let's go with 0.2 MeV, this sort of single dashed line-- you can see that the probability of back scattering is somewhere between the 3 MeV and the 10 keV. Yeah, Luke?

AUDIENCE: Back scattering refers to the photon going back.

MICHAEL SHORT: That's right. Back scattering refers to the photon going back, which means this situation, where the difference in angle between the incoming and outgoing photon is pi, 180 degrees, which means it just turns around and moves the other way. Right. So that dashed line right there would follow something like this at-- what did we say? 0.2 MeV.

The form, the full form of this cross-section right here is referred to as the Klein-Nishina cross-section. And it has been derived by quantum electro dynamics, which I will not derive for you now. But there are plenty of derivations online if that's your kind of thing. And I had to make a trade-off in this class of how deep do we go into each concept versus how many concepts do we teach? And I'm going for the latter because if there is any course that's supposed to give you an overview of nuclear, it's 22.01. There will be plenty of time for quantum in 22.02 and beyond, should you want.

At any rate, this is the general form of it. And what this actually tells you is that as the energy of the photon increases, the effect of that angle will-- you guys'll have to work that out on a homework problem. I just remembered. I want to stop stealing your thunder and giving away half the homework. Yep.

AUDIENCE: How does [INAUDIBLE]?

MICHAEL SHORT: Yes.

AUDIENCE: --the quantity D sigma D omega.

MICHAEL SHORT: The quantity D sigma D omega says let's say you have a photon coming in at our x-axis. You've got an electron here. What's the probability that I'm going to scatter off into some small area d omega? So in some small d theta d phi, or some small sine theta, d theta d phi, into an element of solid angle. I should probably draw that smaller to be a little more differential looking.

So gammas are going to scatter off in all directions. But this d sigma d omega tells you what's the probability that it goes through that little patch?

AUDIENCE: And then that omega is also a function of [INAUDIBLE]?

MICHAEL SHORT: So that omega has some component of theta in it and some component of phi in it. Since it's a solid angle, it depends on both the angle of rotation and the angle of inclination, which we call theta and phi. Now to get from this to the regular cross-section you're used to, you can integrate over all angles omega of the differential cross-section, and you'll get the regular total cross-section, which is just what is the probability of Compton scattering, full stop.

If you wanted to know, then, what's the probability of Compton scattering into this angle, it sounds kind of boring, right? Why do we care about the angle? Anyone bored yet? You can raise your hands. Be honest. Interesting. OK. Well, I'm going to tell you why it's not boring because I don't think you're honest.

You can actually, if you know the angle at which a Compton photon scatters into-- actually I want to leave that stuff up-- there is a pretty much one to one relation between the energy and the angle of scattering, which means that let's say you have a cargo container. I'm sorry. You don't have a cargo container. You have a cargo ship full of tons and tons of these stacked up cargo containers. Has anyone actually ever seen one of these before?

OK. In case not, I'm going to do something dangerous and go to the internet. And hopefully the search for cargo container doesn't come up with something disgusting. Oh, look at that. How about cargo container ship? Yeah. OK. You got one of these, right? And your detector goes off, and it just says there is something radioactive that shouldn't be here. How do you find out which container it's in without taking the ship apart? Interesting problem, huh? Do you just kind of look-- yeah?

AUDIENCE: Do you kind of like shield certain angles [INAUDIBLE]?

MICHAEL SHORT: That's one way. You could mask off the ship and move your detector around, and then do it for the other two dimensions. So that will get you there, but slowly. How do you do it quickly? Well, you do it with the Klein Nishina cross-section. If you know the relationship between the energy and the angle of a Compton scatter, you take two detectors, Detector 1, Detector 2, and you form what's called a Compton camera.

This is awesome because with two detectors, you can pinpoint the location of a radiation source by knowing-- let's say you had a gamma ray that entered Detector 1. So you have your initial e gamma. And you get a spectrum. Let's draw a couple of spectra. I'm going to use different colors so I can make them bigger. This will be intensity and this will be energy.

So we have our blue Detector 1, and we have some spectrum for Detector 1 where we get the photo peak of the gamma at e gamma. And this time, you don't see every possible angle. You only see whatever angle you get that Compton scatter at. Or you might see a whole bunch of different angles. Never mind. So you're going to see the Compton edge in this whole continuum of things.

And so you know that whatever energy this corresponds to means that theta equals pi. That energy corresponds to theta equals 0. And you know that there's a source somewhere in here. Now let's say that photon scatters out of Detector 1 and into Detector 2. In this case, you've no longer just know that you have a source of some sort. You'll end up with a certain photo peak corresponding to this e gamma prime, the only energy that can Compton scatter in the direction from Detector 1 to Detector 2, because you have now determined the angles between the line between the detectors and the detector at the source.

So then you get a photo peak and the corresponding Compton edge for your e gamma prime. Your e gamma prime, that tells you the angle that it came off of for your first interaction. So that is your source angle. So what that means is that by using these two angles, you've now pinpointed your source to lie somewhere on these two cones projected back on one of the two points where those cones at that angle intersect.

This is something I want you to try and think about and work out on your own. But it's really cool to explain this because with one detector, you know that there's a source somewhere, and you know generally where to point. With two detectors and energy resolution, the energy of the photo peak of the second event tells you what the angle of the first event was.

And this way, if you know what source you're looking for from the first photo peak, and you know what angle you're looking for from the Compton scattered photons photo peak, because they have those, then you know not only what the source is, but where it is. And you know which container should take a part to start looking.

So this is why we care about angle, because there's actual, real ways of using this to your advantage to solve some pretty insane problems, like which container would that be in. Who's starting to get the general idea behind a Compton camera, or who would like another explanation? Anyone? I asked two questions. So who would like another explanation?

Yeah, OK. The idea here is with just one detector, all you know is whether or not there is a source. The only information you're getting is its photo peak and Compton edge and bowl. And so you know the identity of the source. Maybe it's cobalt 60 or something. But you don't know where it is. By making a second measurement, you can then determine where on the Compton spectrum of the first measurement does the photon lie.

So by saying OK, the photo peak corresponds to this energy, which corresponds to some certain angle that this had to scatter off of. So then you know what this angle is. You've determined theta.

AUDIENCE: Is that the same theta that you just drew as theta angle?

MICHAEL SHORT: Yes. OK. Angle. You've then determined this angle because you know the incoming path of the photon, and you now know the outgoing path, which means you know angle. So if you know the line between these two detectors, and your photo pick lines up with your first Compton spectrum's angle, you then look at that angle back. You also have to sweep around in the other direction, which means you end up with a cone of possible locations. Yeah.

AUDIENCE: How do you know that the photons that get to the second scatter from inside the first one?

MICHAEL SHORT: There can be only a couple of things that could happen, right? You could have another direct photon just shoot into Detector 2, in which case you'll just get a little bit of photo peak. But we know to expect that, so we can ignore it. We're specifically looking for the photo peek coming from Detector 1.

AUDIENCE: So they wouldn't just go in the air and do Compton scatter [INAUDIBLE]?

MICHAEL SHORT: They would, which gives the perfect pretext to bring up the cross-sections for these processes. So I'm going to skip ahead a little bit and start getting into what do the actual cross-sections look like for Compton scattering, photoelectric, and pair production? All of them have to do with the electron density of the material. The more electrons in the way, the more you get these events happening.

So yes, you will get Compton scatters in the air because air contains electrons and they do Compton scatter. But air is not very dense, so you will get comparatively less. So let's say that adds a little bit of noise on the bottom, which is like any detector spectrum we've ever seen. There's always noise from all sorts of other processes we're not looking for.

So now let's start to look at what the general energy and z ranges of each of these effects are. And we're going to recreate one of the plots that I showed you at the beginning of yesterday's class. So let's make a graph of energy of the photon and z of the material. And we want to try to map out where the following three processes are dominant. So tau, our photoelectric effect. C, which we'll call our Compton scattering. And kappa, which we'll call pair production.

And these cross-sections do give us relative probabilities as a function of the energy of the photon and the medium they're going through, along with the actual density, that something's going to happen. So let's look at the form of these. The cross-section for the photoelectric effect scales with z to the 5th. Do you think that photoelectric effect will be more likely for low z or high z materials?

AUDIENCE: High.

MICHAEL SHORT: High z materials, right. So we know we're going to be in the top half area. And it scales with one over energy to the 7/2. So do you think this will be most likely with low or high energy?

AUDIENCE: Low.

MICHAEL SHORT: So lower energy. So we're going to fill in our photoelectric somewhat. Oh, I'm sorry. So we know it's going to be in this part of the z. We know it's going to be in this part of the energy curve. So let's fill in that area as photoelectric.

Let's look at the other extreme, pair production. It scales with z squared, so is that going to be in the low or the high z area?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: I think still high, just the bigger the z, the bigger the cross-section, right? So we know that pair production is going to be in the high z area. Now how about the energy? It scales with the log of energy, but the energy is on the top. So will a low or a high energy give you more pair production?

High. So pair production is going to be here, leaving everything else for Compton scattering. And if we jump back to the start of last class, we've reproduced from the cross-sections the same sort of plot that we saw before just from looking at the relative probabilities of each effect, which I think it's pretty cool. We can now do that with some basic physics knowledge.

Last thing I want to fill in for Compton scattering is that the Klein Nishina cross-section, which is your differential cross-section as a function of omega, combined with the probability that you scatter into a certain angle and a certain energy-- because there's a one-to-one relationship-- ends up giving you your d sigma c over de, which is your energy distribution of Compton recoil electrons.

And that's directly what leads to the shape right here, where if you have, let's say, 0.51 MeV, relatively low energy, there's-- let's see. What do I want to say here? Yeah. So as you go up in higher and higher energy, you get fewer and fewer Compton electrons, because like Jared was saying, the probability of a Compton interaction does go down with increasing energy, as we kind of reasoned out.

But in addition, you get relatively more of these back scattered ones, which is kind of interesting. I have to think about that one. But this is the typical shape that you tend to see for Compton scattering. For high energy photons, you get a Compton peak and then a very long, shallow tail. And as you go lower and lower energy, it starts to sort of bounce back up. And yeah, Luke?

AUDIENCE: When Compton scattering happens, are the electrons being knocked off the atom?

MICHAEL SHORT: Oh, yeah.

AUDIENCE: OK. So how is that different from the photoelectric effect?

MICHAEL SHORT: The photoelectric effect is an absorption followed by an injection. In Compton scattering, the other photon is still intact. It just loses energy, gains wavelength. But the energy of Compton scattering is-- let's say, for MeV photons, it's on the order of hundreds of keV-- plenty to eject most of the electrons from an atom.

So you always have to think about are you going to eject something? Are you above the work function? Work function for most atoms-- so we had a nice plot of that-- is in the eV range. So chances are, yeah, Compton scattering mostly is going to be ejecting electrons, too. That's the whole reason we can count them. If there wasn't an electron ejection, there would be no electron ionization cascade to count. So there's some sort of empirical or experimental proof that it does happen.

And speaking of experimental proof, you can actually see that shape. In this case, this is a spectrum taken from two different gamma sources together, a-- what is it, 1.28 MeV and a 0.51 Mev. And you can see that the 1.28 MeV, first of all, has a way lower number of counts, showing that the cross-section does, indeed, decrease with higher energy.

And it doesn't have-- well, you can't really even see-- but it does not curving back up, whereas this lower energy Compton photon is scattering more often because it's much higher, and it's got that bump back up at the really low energies.

So it's kind of neat when the math that we're looking at, if I jump ahead to the cross-sections, you can see that you'd expect the Compton scattering to decrease with energy. And you look at an experimental plot of two different energies, and there you have it, higher energy, less total Compton scattering, but different shape.

So any questions before I move on to how you can use them to design shielding?

So what we're getting here, these cross-sections, are probably better known to some of you as mass attenuation coefficients, which are simpler ways of describing how many photons in a narrow beam would undergo some sort of process and be removed from the beam.

And they get removed exponentially for the same sort of reason for pretty much everything in this class ends up being an exponential, doesn't it? Where if you have some intensity of photons or some change in intensity that's proportional to a change in x in the initial-- let's see-- and some-- what is it, concept of proportionality like the cross-section, or we'll call it now mu, this mass attenuation coefficient.

The answer to that ends up being pretty much the same. And it's this simple exponential thing. And the nice thing is you don't have to calculate all these different cross-sections because they're tabulated for you by NIST. And that's one of the links on the website, on the learning modules website that I want to show to you guys now. You can actually look up these total summed cross-sections for gamma ray interactions as a function of energy versus their mass attenuation coefficient in centimeters squared per gram.

The reason it's in that unit is it just tells you what the material does. It doesn't tell you how much you have in the way. And that's why I've rewritten this exponential attenuation formula with a rho on the bottom and a rho on the top, that rho being the density of the material because usually you can just say, it's like i naught e to the mu x. But these are the things that you'll look up in tables. And these rhos right here is whatever density you have of your material.

So if you want to calculate how much better cold water is shielding than hot water because of its change in density, you can then look up the value for water, which I want to show you how to do right now. Back up to see the actual site. So if you guys looked right here, these-- what is it-- NIST tables of x-ray absorption coefficients.

I'll show you how to read through this table now because you'll need it from everything from problem set 5 to the rest of your life. This is one of those places you're going to go constantly looking for nuclear data. So you can either look at elemental media or compounds and mixtures, water being one of them.

So let's go down to water, liquid. If you notice what's actually given here is this view over row. So the nasty, what is it, density specific mass attenuation coefficient. In other words, it's a cross-section, really. It's a microscopic cross-section. I don't know why, in a lot of these courses, they're introduced separately because they're the same thing. They're interaction probabilities.

And then that other rho from the slides just tells you how much is in the way. That rho times x just tells you how much water's in the way in terms of how dense it is and how thick your water shield is. So using these tables, if you know, let's say, you're sending in one MeV photon, so we look up 10 to the 0 MeV-- you then have this value, this nice round value of 10 to the minus 1 centimeters squared per gram.

You then multiply by the density of the water that you have multiplied by the thickness of your water shielding, and you get the change in intensity of the photons. And let's do an example calculation just to make it a little more real.

So let's say we have a beam of photons of intensity i naught. And we're sending it through a tank of water. And the question is, do you want to keep this water at 0 Celsius or at 100 Celsius? What's the difference in shielding between freezing and boiling liquid water? Well, we can look that up. And let's say we have to specify an energy of the photons. We'll call it 1 MeV photons.

So we can look up and say at 10 to the 0 MeV, we go over. We get just about 0.1 mu over rho.

So mu over rho equals 0.1 centimeters squared per gram. And now we can set up two equations, one for 0 Celsius and one for 100 Celsius.

So we'll say i at 0 C equals i naught. E to the minus 0.1 times rho at 0 Celsius times x. Let's say we have, I don't know, 10 centimeters of water. So we'll just put a 10 in there. That works out pretty well. And then our i at 100C is the same i naught times e to the minus 0.1 times rho of water at 100 times 10 centimeters.

And keep in mind here, I made sure that since my mu over rho units are in centimeters squared per gram, I'm putting in x as 10 centimeters because whatever is up here in the exponential has to be unitless. That's a good check to see why are my calculations off by a factor of a billion? Just check the units in the exponential. Yeah.

AUDIENCE: Wouldn't the value of 0.1 change for your cross-section [INAUDIBLE]?

MICHAEL SHORT: The value of 0.1 will change depending on the energy of the incoming photons.

AUDIENCE: I mean, for the density.

MICHAEL SHORT: Nope.

AUDIENCE: Density changes, right?

MICHAEL SHORT: Density changes. And that's what we account for here with this rho. So next up we have to look up the densities of water at 0 and 100 Celsius because I don't actually know them. So density of water at 0C-- oh, surprise, surprise-- it's we'll call it 1 gram per centimeter cubed. Now what is it at 100C? Too close to tell. Actually. That's interesting. At 0 it's a little lower.

AUDIENCE: No, I think that--

MICHAEL SHORT: I think that site's wrong.

AUDIENCE: It's definitely lower at 100C.

MICHAEL SHORT: Yeah.

AUDIENCE: I don't think that second Google result is talking about 100 degrees C.

MICHAEL SHORT: Let's look at some steam tables because this is a real place to look for them. So water is 100. Celsius atmosphere is-- OK, we'll just see that. I think they're down here. Oh, the chalk's not letting me use the touchpad. That's kind of cool.

AUDIENCE: [INAUDIBLE] water at 100 degrees Celsius?

MICHAEL SHORT: Oh, there we go. Yeah, I think I got it. So what's the density of saturated liquid? 0.958. 0.958 grams per centimeter cubed. Wow, I actually used the last corner today. Awesome. So you can actually, then, go ahead and calculate because-- I love how this worked out, right? 0.1 in 10, cancel. 0.1 in 10, cancel. So we'll just do e to the minus 1.

And we get that this i is about 36.79% of the gammas will be transmitted through 10 centimeters of water. And here, e to the power of negative 958, we get 38.37% transmission. So actually, about 2% more of the gamma is will be transmitted if the water is hot. It's a neat little calculation that you can do.

Now we've looked at a really fine, or very small magnitude example. Folks came to me yesterday saying we want to design a new type of medical x-ray apron because we're worried that people carrying around all this lead, their backs are hurting and it's making surgeons' lives difficult if they're doing radioactive procedures. Can we do any better?

Can they do any better? What do you guys think? Can you beat physics when it comes to mass attenuation? It's going to be awfully difficult. And the best weapon you have is these mass attenuation coefficients to look at their relative values. Now these, again, are in centimeters squared per gram. So this actually ranks aluminum to uranium in a sort of like per atom basis. It has nothing to do with their higher densities, which only help things. This just tells you how effective each of these elements is relatively at blocking gammas of different energies.

Then, to get the total amount of attenuation, you multiply by the density. Aluminum is pretty sparse. Lead and uranium are pretty dense. There's not too many ways around this problem. In fact, I wouldn't say that there's a way around this problem. The best thing you can do is look at the really only interesting features on these curves. Does anybody know why there's those jagged edges there?

Well, let's take a look at some trends. For uranium, the jagged edge is at about 110 keV. For lead, it's like 80 keV. For tin, it's probably more like 50 keV. It's decreasing with z. Anyone remember what sort of magnitude? We've looked at things like this before. And if we're talking about photon electron interactions, what could be responsible for those sudden jagged edges?

Well, we have talked before about all sorts of different decay methods, including those that can eject electrons from different energy shells. You're looking at the same electron energy shells. If you have a, let's say, photoelectric capable photon entering a calcium nucleus-- and let's go look at calcium as an example. So I'll go to the tables of coefficients. I'm going to back up to elemental media. And I'm going to go to calcium for a simple example.

Calcium has got this jagged edge right here. And if we draw a line down, it is precisely 4 keV. 4 keV, I bet, is going to be the k edge energy, the energy of the most inner bound calcium electron. To find out, we can go to the other NIST page that I linked you guys to, the NIST X-ray Transition Energy Table. And let's look at calcium. Wow, this really doesn't work with chalk on your fingers. And let's look at the k edge to check.

Lo and behold. 4.05 keV. So what you're seeing here is the photoelectric peak k edge absorption. What this says is at energies below 4 keV, you can't inject the innermost electron. You just don't have enough energy. As soon as you hit 4 keV, those inner shell electrons become accessible to you. So the cross-section suddenly jumps up because you have more electrons that you can inject photoelectrically.

Beyond 100 keV or so, there's no more jagged edges because any photon above 100 keV can access pretty much any electron in any element, except maybe the super heavy ones, and we don't have data for them yet. So then you might ask, well, there's going to be an L edge for calcium. Where would that be? Probably off this chart. But you can look up where it would be.

So we'll go to the NIST-- yeah. So you had the right idea, Dan. To the left, right? Yeah. Exactly. So now let's look up the L edge. So if I were to ask you-- wow, it really doesn't work with chalk. OK, that's better. So the L1 edge is down at 438 eV, which is indeed off the scale for this graph. This bottoms out at 1 keV.

But if I were to ask you to draw the full mass attenuation coefficient for uranium, I'd expect to see a k edge, an L edge, an m edge, and an n edge corresponding to shell levels 1, 2, 3, and 4. And where do you get that data? You get it from here, from this NIST databases. Or you calculate it one at a time using that Rydberg formula, where that n final goes to infinity.

So you can either calculate them if you don't know. Or if NIST doesn't have them in the table-- and I don't think they have the n edge-- wow, they go all the way up to fermium. Let's do uranium. What do they go to? Yep. They don't have the m or the n edge. But you do know how to calculate them, is with that formula. And so if we were to construct any old mass-- what is it, mass coefficient-- good, we have a little space left.

It's going to look generally like this. There's going to be a photoelectric region. Let's say that's going to correspond to our photoelectric cross-section, which goes way up with lower energies. There's going to be a pair production part, which goes up with higher energies. And there's going to be this kind of decreasing Compton cross-section.

And if you kind of dance these curves, you end up with a shape like that, which is just like all the other mass attenuation coefficients that you see. So this is why they take the shape that they do if you add up the cross-sections for photoelectric effect, Compton scattering, and pair production, and you just kind of bounce on top of those, you end up with the mass attenuation coefficient. And the part that's not shown here is that this photoelectric effect will have some jagged edges whenever you hit an electron energy transition level.

So it's five of. Want to see if you guys have any questions on photon interactions with matter. I know it's a lot to throw at you at once, but I'm going to be giving you guys lots to calculate, to try it out and to learn what's going on from a more hands on point of view. Yeah.

AUDIENCE: So you can't, I guess, beat physics by increasing density of materials. Is there a way to slow down gammas?

MICHAEL SHORT: Is there a way to slow down gammas?

AUDIENCE: Besides relying on [INAUDIBLE]?

MICHAEL SHORT: Yeah. So the question is, can you slow down gammas without putting stuff in the way? Well, then, what are you doing? You've got a vacuum, right? So-- hmm. That's probably a deeper question than I think. So gammas, for example, do have indices of refraction and materials. Gammas are just photons. They're just really high energy. And they do have indices of refraction that are usually around one part per million, or like 1.000001 or so. So you can refract or bend gamma. Just not very well.

So the question is, could you do something to stop the gammas that were maybe 10 feet away? The answer is physics. Not much you can do. But if they're, like, planetary levels away, it's possible that you could bend them away from an object, just like you can bend visible light away from something closer up because it's got a much higher index of refraction.

Pretty crazy stuff. Did you ever think of gamma ray as having indices of refraction and behaving like regular light? It's just regular light. It's just really high energy light. So any other questions on the photon interactions with matter? Cool.