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MICHAEL SHORT: And to try something out a little real, I took a detector that you all have, as well, my cell phone. And this morning I went down with EHS to one of the very radioactive cobalt-60 sources, a 10 millicurie source. If you note, the source that we were playing around here was one microcurie, so this is a 10,000 times stronger source. It was actually able to show the difference between a background count of my phone. You shouldn't see much going on, except for that one malfunctioning pixel, because not much is going on.

And when I put the phone over the source itself, things look a little different. You guys see all that digital noise, or snow in the video? Every one of those white flashes that you see is a gamma interaction with the semiconductor in the cell phone camera, with one or more pixels in your CCD, or charged couple device, or your CMOS detector, whichever one it happens to be.

So I thought this was pretty cool. You can actually use your cell phone as a radiation detector. We're going to understand why, and what sort of radiation it could detect by virtue of its size and its composition today. Anyone ever try this before? You have?

AUDIENCE: Yeah.

MICHAEL SHORT: Cool.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Probably more intense than this if you were making neutrons, right?

AUDIENCE: Yeah.

MICHAEL SHORT: Awesome. OK, cool. So let's just first figure out, well, where is this radiation coming from? This is the link between the first part of the course and what we're going to be doing over the next month. As we've seen from the decay diagrams-- and I think I've harped on potassium-40 as an example for a reason-- it can undergo electron capture or positron release. And if it undergoes electron capture by this likely route it gives off a 1.461 MeV gamma ray as the only

possible transition here.

It also undergoes beta decay, which you don't want to forget about if you're calculating the activity of potassium-40. But today we're going to be focusing on what does this gamma ray actually do when it encounters matter? Or what are the possible things that can happen? I'm going to introduce them conceptually today, and we're going to go through the math of the cross sections and the energetics more tomorrow. So I'm doing a context first, theory second kind of approach.

There's three main things that gamma rays will do in matter depending on their energy and the actual matter itself. There is one called the photoelectric effect, where a gamma ray simply ejects an electron from the nucleus. So let's say we've got our potassium-40 atom, have a bunch of electron shells-- I'm not going to draw all the electrons, but I'll draw a few inner and outer ones here. One of the things that the gamma ray can do is just eject that electron, have it come firing out. And the energy balance for that isn't that hard, because this gamma has some energy E_{gamma} .

This electron had some binding energy, E_{binding} . And the kinetic energy, let's call it t , of the electron is simply the gamma ray in minus the binding energy back out. It's just however much energy it takes to remove that electron, that's what it takes. And so you end up with, if we go back to our banana spectrum, what we call a photo peak, or a photoelectric emission peak, right here. If you trace down this line, it's awfully close to 1,469 KeV, Or 1.46-- what was it? 1.461 MeV.

It won't be exactly at that energy, because it does take a little bit of energy to remove that electron. Anyone have a guess on what order of magnitude that might be? Yeah. KeV all the way down to eV. So this photo peak will typically be extremely close, but not exactly equal, to the energy of the gamma ray coming out. For most detectors that don't have that good resolution, you can pretty much assume they'll be in the same channel, or the same energy bin, because your detector will have some sort of resolution. It may have 1,024 or 2,048 channels that span the full energy range. And you might not be able to tell the difference between 1,460 MeV-- or 1.46 MeV-- and that minus a few eV. Potassium, in particular, has quite a small work function. And we'll get into why that is in a second.

The next thing you can do is what's called Compton scattering, in the general case, which means that there is an electron here. A gamma ray comes in with E_{gamma} . And then it

bounces off with some energy, E-prime-gamma. And then the electron goes off with some other kinetic energy. Then the last one is what's called pair production. Just like in the Q equation, if you have anything related to positrons you have to first create them. So pair production doesn't happen below about 1.022 MeV.

And it happens with increasing probability as the energy of the photon goes up, kind of like in radioactive decay. There's a lot of parallels here. Is you can make an electron-positron pair at 1.022 MeV. It's just not very likely. And what we're going to find out tomorrow is why the most likely photon effect is shown in these different regions. Anyone have any idea? Why do you think the photoelectric effect would be most likely at low energies and high Z? You just have to give an intuitive guess. Yeah, Luke?

AUDIENCE: Because the binding energy isn't very large for the outer electron shells.

MICHAEL SHORT: That's right. So that explains the low energy idea. So it doesn't take very much. In fact, does anyone know what the minimum energy you need to make the photoelectric effect happen? Well, what's a typical order of magnitude for binding energy of the lowest, or the outermost, electron shell, or the lowest bound electron?

AUDIENCE: Work function?

MICHAEL SHORT: Yeah. That's called the work function. Anyone know an order of magnitude, guess what it is? It's in the single eV range. In some cases, it can even be slightly lower. And that, we're talking about visible light. So green light, even yellow light, can eject electrons via the photoelectric effect. And then the reason that goes more likely with higher and higher Z, we'll get into that when we look at the different cross sections of interaction.

Pair production is much more likely at higher energies, because at higher energy you're more likely to create a positron. And in addition, pair production happens when a photon interacts with either the electron cloud, or the nucleus there. And that gets more and more likely, let's say, the denser the electron cloud is or the higher charge there is on the nucleus. So first, the simplest one, the photoelectric effect, this is actually what Einstein won the Nobel Prize for. Not E equals mc squared, which has been the bane of our existence for the last month.

That's not what he got the Nobel Prize for. It was demonstration of the photoelectric effect, where if you start firing photons of an energy times Planck's constant times its frequency-- and in the next page I'll give you a quick photon math primer, in case you don't know what those

quantities are-- there will be no photoelectric emission until you hit that work function. Yeah, like Julio was saying, that lowest bound electron energy. And then, emission will simply go up. And so this was demonstrated by applying a voltage to two different plates, two different metal plates, and then sending in light via this window and seeing when the current actually became non-zero.

So the way you detect photoelectric emission is, if you've got electrons boiling off of one surface to the other, that's the movement of charge, and that's a current. And so you can measure a current with an ammeter. That's-- it actually is that simple. But very elegant experiment, back for the 1910s or 1920s. And as a quick primer on photon quantities, so you know what all of these different symbols mean, the photon energy we give as Planck's constant times its frequency. And I gave you Planck's constant right here, for reference.

I do recommend that you guys try checking out all the units to make sure that they work out. Because if you ever forget, is it h times ν , or is hc over λ , you can always check the units of your expression to make sure they come out to an energy. Which in SI units is what?

AUDIENCE: Joules?

MICHAEL SHORT: Joules. And then how about in these sorts of things, the most reduced SI units?

AUDIENCE: eV?

MICHAEL SHORT: Is what?

AUDIENCE: eV?

MICHAEL SHORT: eV is another unit of energy similar to the joule, like 1.6×10^{-19} joules. But what about in meters, kg, seconds, other SI units?

[INTERPOSING VOICES]

MICHAEL SHORT: Yep. Kilogram meters squared per second squared. Indeed. Per meter squared, per second squared. Yeah. So just make sure sure you remember that, because if you're just looking for joules and you don't remember what a joule is, it's going to make unit balance kind of hard. And also, we can describe the momentum, or p , of the photon as Planck's constant over λ , its wavelength. This is going to get real important when I ask you guys to do a derivation, much like the q equation one that we were doing before. But instead of me just

doing it at the board and you copying it down, I want you guys to try working through it. And it's going to be another energy and momentum conservation thing, just like before. And this way you know what the energy is and you'll know what the momentum is.

So now onto this work function. What is it, actually? There's a great paper by Michaelson-- I did not look up whether this is the Michaelson of Michaelson Interferometry, but I wouldn't be surprised. I'm going to check into that. But I did dig out this paper that actually shows the different patterns in the work functions of different elements. So what do you guys notice in terms of patterns, here? First of all, which elements are all the way to the left or have the lowest work function?

AUDIENCE: Group one.

MICHAEL SHORT: The what?

AUDIENCE: The group one metals?

MICHAEL SHORT: The group one metals, like sodium, lithium, potassium. Why do you think that is?

AUDIENCE: I mean, they have-- I don't know.

MICHAEL SHORT: They've got one electron in their outermost shell. So it looks like my potassium picture is not quite accurate. I'm going to draw another shell, and put one lone electron in that for accuracy. And so that electron is extremely unbound. That's the same reason that these elements are so chemically reactive. They want to ditch that electron to have a filled outer shell. So you may also expect the work function of noble gases to be extremely high.

I don't know if any are plotted here, but you do see the next row over, like barium, strontium, calcium, magnesium, has a slightly higher work function. And as you move this way through the periodic table, to the left, until you hit the transition metal craziness, it follows a pretty regular pattern. And so you can have a good guess of what the work function of something will be depending on its Z , and depending on which-- what is it? Which column it's in in the periodic table. Now, can anyone tell me, why do you think that work functions tend to increase with decreasing Z ? Yeah.

AUDIENCE: For smaller Z , the outermost electron is closer to the nucleus, so it's more tightly bound.

MICHAEL SHORT: Indeed. Yep, exactly. For the smaller Z , that first or second shell is a hell of a lot closer to the

nucleus. Even though it has a lower total charge in the nucleus, it's much more tightly bound, being much closer. So, like the outermost electron in caesium is quite far away, it does not feel as much coulomb attraction. Yeah, good point. So now onto Compton scattering. I'd say though the most difficult, conceptually, to understand the energetics. But the kinematics, or what actually physically happens, should look strikingly similar to what we've spent the last month on. Instead of two particles colliding, it's a photon colliding with an electron.

Does anyone remember what we read in that first day of class, with the Chadwick paper? When he said, hey, maybe this quantum of energy is done in a process analogous to Compton scattering. Well, this is Compton scattering. His analogous process was maybe an electron hits a proton and something happens, which is not actually what happens. And in this case, you have a photon with energy $h\nu$, and momentum $h\nu/c$, striking an electron with rest mass m of electron c^2 , or 0.511 MeV. And afterwards, the photon leaves at sum angle θ , and the electron leaves at sum angle ϕ .

So I'm going to show you guys some of the Compton scattering energetics relations, like what is the wavelength shift. Which means that if this photon comes in with a certain wavelength, λ , and it gives some of its energy to the electron, it comes out at a different wavelength. Is it going to be lower or higher wavelength, do you think?

[INTERPOSING VOICES]

MICHAEL SHORT: I heard a bit of both. So who says lower?

AUDIENCE: Me. It can be wavelength.

MICHAEL SHORT: So lower wavelength. Let's go back to the photon formula. Would a lower wavelength result in a lower or a higher photon energy?

AUDIENCE: Higher.

MICHAEL SHORT: OK. So in a Compton scatter, you start off with an electron kind of at rest. They're definitely not actually at rest. But compared to the energy of the photon, they're at rest enough. And then you give some of that energy to the electron. That energy has got to go down. And because these two quantities here are constants, the wavelength has got to increase. And hopefully this makes intuitive sense. The photon does what we call a redshift. It shifts closer to the red end of the visible spectrum than the blue end.

And as you guys know, the high energy light in the visible spectrum hits towards the ultraviolet. That's what tans you, or gives you skin cancer. Red light, or infrared light, doesn't do much of anything at all. And so this is that on the extreme scale, where when we say redshift, we don't necessarily mean the photon is visible. But we do mean that it's shifting to a lower energy, or a higher wavelength.

And so this wavelength shift is always going to be, well, is it going to be positive or negative?

AUDIENCE: Positive, right?

MICHAEL SHORT: Is what?

AUDIENCE: Positive?

MICHAEL SHORT: So you say the wavelength shift is going to be positive, which would mean an increase in wavelength? There you go. Yep. Because it's got to be-- it's got to lose energy. So I'm not going to go through the derivation of these, because I want you guys to go through the derivation. But we're going to do it in the exact same way, and I'll help kind of kick you off. Where, in this case, what are the three quantities we can conserve in every physics, everywhere?

AUDIENCE: Mass, energy, and momentum?

MICHAEL SHORT: Mass, energy, and momentum. The trick here is, what is the mass of the photon? Massless. So we've got energy and momentum. And we've got, let's say, some wavelength shift to determine, which is some change in energy. And we've got two angles to deal with. That's three unknowns. We need three equations. So we know that our initial energy coming in is going to be $h\nu$ plus approximately 0 becomes $h\nu'$, and the kinetic energy of the electron. So that's our energy conservation relation.

And then what do we do about the momentum? What do we do last time?

AUDIENCE: Split it into x and y.

MICHAEL SHORT: Exactly. Split it up into x and y momentum. So the x momentum of the photon-- so I'll just label this as energy-- put the x momentum of the photon is $h\nu/c$. And there was no x momentum of the electron to begin with. So then we're going to say this has outgoing momentum $h\nu'/c \cos\theta$ plus whatever the electron momentum is,

let's say m electron v , or $\sqrt{2} m$ electron, T electron, $\cos \phi$.

And then how about the y momentum? What's the y momentum of the system at the beginning?

AUDIENCE: Zero?

MICHAEL SHORT: Yep. Nothing for the photon, nothing for the electron. And at the end we've got $h \nu$ over c $\sin \theta$ minus, because it's in the negative y direction, momentum of the electron $\sin \phi$. I'm going to stop my part of the derivation there, because I don't want to steal away your whole homework problem. But you're going to start it out exactly in the same way as we were doing kinematics of two particle collisions. Because what is a particle, but a wave? They're all the same thing. It's modern physics.

And then-- here's an interesting bit, here-- this maximum wavelength shift, if you want to figure out what is the-- well, look. Let's say, we call it the Compton wavelength. So if you were to decide what is the maximum wavelength shift, where would that be? At what angle? Did you have a question, or did you say what was the question?

AUDIENCE: Yeah.

MICHAEL SHORT: Oh, OK. Is what?

AUDIENCE: π over 2.

MICHAEL SHORT: Is that angle π over 2? Because at that point \cos of π over 2 equals zero. Yep. And so then you get this interesting result. No matter what the incoming energy of the photon is, you get this 0.238 MeV shift. And that's actually going to help explain, to jump back to our banana spectrum, what the distance is between our photo peak-- which is our photoelectric peak, which is pretty close to the energy of the photon-- and this part right here, which we call the Compton edge. Which would mean the maximum scattered energy of that photon, in this case. Or no, I'm sorry. That would be the maximum energy imparted to the electron. Almost misspoke there.

And no matter what this energy of the photon is, that distance right there, that's the Compton wavelength. Interesting quirk of physics, huh? Because in the end, all that matters is if the angle's all the same, everything else cancels out and you just get a bunch of constants. Let me jump back to there.

So now we'll take another look at our detector spectrum and start identifying some of these peaks. If you notice, this 0.238 MeV looks just like what it does on the graph. This is the kind of cool thing, like you guys threw some bananas in a detector last week. We got a spectrum yesterday morning, and how well-timed it was. We're actually going to start explaining it today. There's a whole lot more going on in this banana spectrum. Part of what we'll be explaining tomorrow is, why do you get this kind of bowl shape, this Compton bowl?

And it turns out that there's a different probability of scattering at every different angle, or what we call a differential cross-section. $d\sigma/d\Omega$. Because the probability of that photon scattering off in any direction is not equal. But if you know what direction the photon scatters off in, you know what energy it has, or you know what sort of energy it gives to the electron, because that's a one to one relation. And that's why you end up with this very smooth, almost cosine-ish looking kind of curve. You guys will actually get to derive that yourselves.

So then onto the wavelength and energy shift. By looking at the electron recoil energy and this wavelength shift, from that you can actually get some sort of an energy shift. You can arrive at what is the recoil energy of that electron. And so here's one of the topics that's usually hard for folks to understand, but I want to stress it right now. When you send gamma rays into a detector-- let's draw an imaginary detector. In fact, let's draw the real one that we used in our banana counting experiment. So we had these copper walls, we had our bag of bananas, and we had our high purity germanium detector.

Let's say we had a good shield on top, and then a good shield on the bottom. That right there is our active detector, and this banana is sending off gamma rays into that detector. The way a detector works is not by counting the energy of the gamma ray directly. It can't actually do that. In this germanium detector you've got a huge voltage applied across it. I think what Mike Ames actually said was the one we used was about 2000 volts.

What happens here is, let's say-- I'll actually need three colors for this-- let's say a gamma ray comes in-- that's our gamma ray-- and interacts in the detector. That gamma ray will redshift-- let me get a redder color, because that'll be like physically accurate-- that gamma ray is going to hit an electron, go off at a different angle, and redshift, or get lower in wavelength. Meanwhile, that electron that it hit actually goes flying off and in the other direction, we're going to call it a hole. A defect missing one electron of some sort in this semiconductor.

Normally if there was no voltage applied here these two would just find each other and annihilate, and you would have nothing. So what's to count?

But by applying a gigantic voltage, let's say this voltage was really plus and this voltage was really minus, this electron keeps on moving and this hole keeps on moving to the electrode. Instead of recombining in the detector, they're actually then sent through where they're counted in some sort of ammeter or some sort of energy pulse counter. And what we're actually measuring is the recoil spectrum of the electrons that the photons make. You're not directly measuring photon energy, you're measuring the electron effects.

Part of that is because chances are photons just go through everything. This is why I wasn't so worried this morning standing with my face over a 10 millicurie cobalt source. Because while I was getting billions of gammas per second flying through my brain, most of those billions just flew out the other side. It's literally in one ear, out the other. And so most of these gammas, if they interact at all, will escape again. The electrons, however, because they're charged and very low mass, have a very low range in the detector.

So chances are the electrons that are made are going to stay there, unless you happen to make one, like, right here at that surface few atoms, and it escapes. That almost never happens. So forget that. This was, last year, a huge source of confusion to say, why are we seeing some of the other peaks that I'll be explaining in five or 10 minutes? Or, why aren't we seeing a 0.238 MeV peak?

Because what you're seeing here is a photon losing its energy minus 0.238 MeV in its maximum energy transfer, which is given to that electron. Then what actually happens next is this electron slams into a bunch of other ones, and that slams into a bunch of other ones until all the energy is lost in the detector. And all of those electrons get sucked into the electrode by this very high voltage. And then, the way you count the energy of an interaction is by how many electrons you get in a certain little amount of time.

And so that's why, for example, for the photo peak, that's the kind of simplest reaction. A gamma goes in, a really high electron comes out, it smashes into tons of other electrons imparting all of its kinetic energy in the detector, which is all summed up in a nanosecond, or however long we collect for. And then we say that we saw an energy blip containing about 1,460 KeV of energy.

It all came from that first gamma. And then it was all given to that first photo peak electron,

which then slammed into a whole bunch of others. And they slammed into a bunch of others. And there's this what's called this ionization cascade, where a whole bunch of electrons make a whole bunch more until all of them have too little energy to ionize anything else. And then they're just collected. So that's what we mean by a pulse in a detector. It's not exactly an intuitive concept, because it's not like the gamma goes in and we just count its energy. There's more things that physically happen in here. But it's important for you guys to know, especially when we start to look at pair production.

You guys remember some of this stuff from the positron annihilation spectroscopy? Well, the way we actually know that positron annihilation spectroscopy, or PAS, works is by measuring photons, or their eventual electron recoil, that can only be possible from this process. So as a quick review, let's say you had a positron source, like sodium-22, which naturally undergoes radioactive decay, and forms a positron along with a gamma ray from a very short isometric transition, or IT.

Then that positron bounces around in the material until it reaches an electron. And once it hits that electron, because the positron-- let's see, the rest mass of the positron is the same as the rest mass of the electron, which is 0.511 MeV-- once the two of these combine, they annihilate, producing two 511 KeV or 0.511 MeV photons. And it's those photons at this exact energy all the time that really give it away. Because there's not many other processes that produce a huge amount of exactly that photon. Now that we've talked a little bit about momentum and energy conservation, does anybody know why you get what's called a blueshift or a redshift in positron annihilation spectroscopy?

I'll give you a hint. It goes down to conserving the same thing that we're doing all the time.

Yeah, Kristen?

AUDIENCE: I was going to say, is that something to do with wavelengths?

MICHAEL SHORT: You're close. I mean, technically you're close, if you treat electrons as waves, which you totally can. The electrons themselves do have a non-zero momentum as they're flying about in the atom or around the nucleus. And when an electron collides with a positron, if that electron already has some momentum associated with it, then the center of mass is not at rest. It's moving at some small speed. So this little minus delta energy and plus delta energy accounts for the initial momentum of the electron, which means not only can you tell from the lifetime how many electron looking defects there are, but you can probe electron momentum by

looking at the slight energy changes as positrons collide with electrons.

It's a really cool and powerful technique that uses only 22.01 concepts to probe matter at its deepest level. So what's happening on the atomic scale is, let's say a photon made a positron, and the positron bounces about what's called thermalizes, or just slows down via collisions, via other types of collisions that we'll go into soon, and then gets trapped in a defect, which is a relatively electron-poor place. But it doesn't mean there's no electrons, In every space everywhere, there's a probability that there's an electron there. In a defect not containing an atom that probability is lower, but not zero.

And so by figuring out how long they last, and when those 511 KeV gammas are emitted, you can tell, let's say, what size defect that was. But now let's talk about what happens to these 511 KeV gammas. What evidence do we have that positron pair production actually exists? So before I reveal the labels, can anyone tell me what on this graph suggests that positrons are happening? And there's actually two things. What do you think? Yeah.

AUDIENCE: There's a peak 511 KeV.

MICHAEL SHORT: That's right. That's exactly right. There's a peak at 511 KeV that if I trace that up, I went one over. Yeah, right there. 511 KeV. Is it exactly 511 KeV? What do you guys think? So forget the fact that it came from a positron, let's say a 511 KeV gamma came in somewhere. How would it then release electrons to be counted? It then undergoes photoelectric emission.

So the actual energy of this would be 511 KeV minus the work function of the material. This is one of those tricky questions that you might not even see it on the spectrum, but I want you to physically understand what happens here. It's not like 511 KeV positron photons magically get counted at 511 KeV. They then have to eject an electron, somehow. And for those electrons to be counted, they have to interact in exactly the same way as all the other electrons. There's no difference. What else? Oh, yeah. Luke, you have a question?

LUKE: So, from the banana. Is a gamma ray coming from a banana, and then that gamma undergoes pair production? And then the gamma from the pair production-- I guess, where are the gammas coming from?

MICHAEL SHORT: That was my next question to you. So let's think about this a little bit. We'll start off with gammas being emitted in all directions from our bag of banana ashes. Now the question is, where do these 511 KeV photons come from? If the gamma ray interacts with the detector by

any mechanism including pair production, what are the possible things that could happen? There's three different scenarios.

Let's pick a 511 KeV color. Well first of all, it might just undergo pair production. And it'll release two 511 KeV gammas. Let's see, those are our 511 KeV gammas. And because they're gammas, and they interact with almost nothing, they can get out. So you might end up - your energy that you detect in the detector might be the energy of your gamma ray minus 2 times 511 MeV. This is what we refer to as double escape. Close the quotes like that.

So if this gamma ray right here came in at 1,460 KeV, and the double escape peak-- if it undergoes pair production in the detector and both of those 511s escape, because a lot of them do-- where would you expect there to be a double escape peak on this spectrum?

AUDIENCE: Add that minus 11.022.

MICHAEL SHORT: Yeah. Let's say, add that minus-- so we're at 1,460 minus 1.022. That comes out to about 450 KeV. 450 KeV right here, not much going on, is there? You're not going to see it in every detector. Especially the larger the detector is, the less likely both of those photons are going to escape. So this is where the concept of detector size can tell you whether or not you're going to see every peak that's physically happening. So in this case, the germanium detector is pretty big, it's pretty expensive.

So chances are a lot of those 511 KeVs, even though they're produced in pairs, one of them didn't quite get out. Yeah, Luke?

LUKE: So, the gamma from the banana goes into the detector. And then it produces pairs, and then those pairs are annihilated, and that produces the vibration.

MICHAEL SHORT: That's right. That's right, why don't we write that down in steps for, let's call this pair production in the detector. So step one would be gamma emission. Step two would be electron-positron creation. Step three would be annihilation. Annihilation in the detector. And then step four would be somewhere between zero to two photons escape.

So we have, actually, three scenarios that could happen here for pair production inside the detector. One of them we just described. Where pair production happens, you get annihilation in a very short time frame, like tens of picoseconds or hundreds of picoseconds. Both the gammas get out. That would have produced a 460 KeV peak, which it might be there. But I can't tell if that's a peak or if that's noise. So we don't really know. And chances are, the

reason that didn't happen is because the detector was big.

So our next possibility. What if one of those photons gets out and one of them doesn't? It then interacts via Compton scattering, or photoelectric effect, or any of the possible mechanisms. Then you'll end up with an energy counted equal to energy of the gamma minus only one of those things getting out. And we call that single escape. At what energy would that single escape peak be? Oh.

AUDIENCE: 511?

MICHAEL SHORT: It would be-- that peak would be at the energy the gamma 1,460, minus 511 KeV. So roughly 900 KeV or so. There we go, there it is. That's the second bit of evidence that there is pair production going on. Not only do you have a peak at 511 KeV, which we have not explained yet, but you also have the single escape peak, which is the energy of your gamma minus one escape from a 511 KeV photon. Yeah?

LUKE: When you mean escape, do you mean escapes through the detector, or what is that?

MICHAEL SHORT: Yes. I mean-- when I escape, I mean it escapes the detector and is no longer counted. So it might go and drop somewhere else, but your detector doesn't know it. So what's the third scenario that could happen? What if zero of these photons escape? What energy will you count?

AUDIENCE: [INAUDIBLE].

MICHAEL SHORT: Exactly. So all that's going to happen is it's going to look like the photoelectric effect. In reality, you'll have slightly, slightly lower energy, because you have three work functions to subtract off from the three photons doing stuff. But I would count that as correct. It's going to look just like the photoelectric effect. First, you get that energy minus 1.022 MeV. And then both of those 511 KeV photons interact in the detector by, probably, photoelectric emission. And you just get another count at this channel, right here.

Now the last question I want to ask you guys, where did this peak come from? Under what circumstance would the detector just count 511 KeV? I'll give you a hint. There's a reason I drew gammas going off in every direction.

AUDIENCE: So they don't hit the detector.

MICHAEL SHORT: Yeah. So most of the gammas don't hit the detector. But let's say you had a gamma that went into anything else, like the copper shielding, and it underwent pair production. And one of those gammas made it through the detector. I'm sorry, one of those photons made it through the detector. That's actually where these things are coming from. Because most of those gammas are not heading towards the detector. This is a very small, solid angle. But surrounding the rest of the detector is this really dense copper, and these high energy gammas in this relatively high Z material undergoes a lot of pair production, so it's firing out 511 KeV photons in all directions.

And some of those enter the detector when nothing else enters the detector. And that's why you get this 511 KeV peak right here. So we haven't explained every peak on this graph. Does anybody have any ideas where-- what's that about? Or that? Or those?

AUDIENCE: Cosmic radiation?

MICHAEL SHORT: Yeah. Could be cosmic rays. That's probably what's contributing to a lot of the noise, here, as well as thermal noise in the detector. But what else haven't we accounted for? Now, to bring this a little more into reality, we ran an experiment where we burned bananas. We didn't put a potassium-40 certified source in. We put bananas in. What else could be going on?

AUDIENCE: Other isotopes?

MICHAEL SHORT: Other isotopes. That's right. But you can identify them quite easily, one, by checking to see where you expect the photo peak. So just from the decay diagram, you'll expect to see some interactions or photoelectric effect interactions, at these transition levels. Luckily, you know they're not due to potassium, because potassium has only got one of them. In addition, you should see some very similar features. So if you have a photo peak here, you would expect to see another Compton edge 0.238 MeV away-- and it's kind of hard to tell if it's going on, because that's a rather weak photo peak-- and you would expect, then, for the high energy gamma rays to see another single escape peak-- maybe right there-- and add to the 511 KeV peak, because those are all the same.

So when you take the spectrum of a real thing, and you have to deconvolute it, or take it apart in terms of its constituent interactions, it's important to know what all these possible interactions are so that you can take them apart and say, start off with a photo peak, which should tell you what elements are there. And then you can subtract off the expected amount of Compton scattering, the expected amount of single escape peak, and then see what's left

over, what other isotopes may there be that you haven't accounted for yet.

The last thing I want us to try, as a mental exercise, is to draw two spectra. Let's say, this will be energy versus intensity. And for this I want you to imagine that, at first, your detector is very small. And then I want you to imagine that your detector is very large. And I'm going to keep this visible so you can have this as a mental model. If we had just one isotope, potassium-40, what do you think the spectra would look like for an extremely small detector and for an extremely large detector?

So where do we start?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: That's right. And will there be any difference between the two? Probably not. So small detector, maybe a large detector is going to have a larger intensity. But for the same type of detector, you're going to have pretty much the same thing. What's next?

AUDIENCE: Compton edge?

MICHAEL SHORT: Compton edge. So there's going to be some energy that Compton scattering is going to start out, and then it's going to proceed up, thusly. Is there going to be any real effect of the detector size? Probably not, because as soon as you release that Compton electron, that electron slams into all the other ones, and nanometers or microns of material, and all the energy is collected. What's the real difference going to be?

AUDIENCE: The 511 peak?

MICHAEL SHORT: That's right. So the 511 peak, and the other associated ones. So for a really, really small detector we have the possibility for a double escape peak, a single escape peak, and just more photo peak. What's the most likely scenario?

AUDIENCE: Double escape?

MICHAEL SHORT: Double escape. So if we go down here, let's say if this difference is 1.022 to MeV, you would expect a larger double escape peak. And what would you expect your single escape peak to be?

AUDIENCE: Smaller?

MICHAEL SHORT: Significantly smaller. So let's say this difference right here is 511 KeV. How about for a large detector?

AUDIENCE: Opposite.

MICHAEL SHORT: Quite the opposite. You might expect a tiny or even nonexistent double escape peak, maybe a larger single escape peak. But most of the time you're just going to add on to your photo peak, depending on the resolution of the detector. Because in this case, for a small detector, if you have an interaction inside that volume chances are most of those 511s get out. For a large detector, chances are most of them stay in and undergo their own Compton scattering, or photo peak reactions.

So let's say that all these detectors will also have a 511 KeV. We'll just mark that off. Let's just give them the same height. What else are we missing, if this is an ideal scenario with no noise? Well what are those five-- what can those 511 KeV photons do? Can they make pair production of their own? No. They're not high enough energy. In fact, they're half the required energy. Can they undergo photoelectric effect? Sure. That's probably where we're getting those 511s.

Can they undergo Compton scattering? Why not? There's no minimum energy to scatter. So what you're going to end up with, then, is 238 KeV away. You should have another little Compton edge at a distance of 238 KeV away from the 511 KeV. Now in reality, you probably won't see it because you're going to have other X-rays, you'll have bremsstrahlung, which we'll talk about tomorrow, which is that breaking radiation. You'll have background radiation. And it might be hard to see, but technically it should be there, because any photon of any energy is going to have that same sort of Compton edge shape.

The shape changes just a little bit, depending on the energy of the photon, but you're always going to have an edge. You're always going to have some sort of a bowl. Just how big the edge is compared to the bowl, well, we'll get to that tomorrow. So it's a little after 5 of 5 of. I think this is a good place to stop, because it's the full conceptual explanation of the ways that photons can interact with matter.

So I want to ask you guys if you have any questions based on what we've done today? Yep?

AUDIENCE: So 511 KeV's the rest mass of electron?

MICHAEL SHORT: Yep.

AUDIENCE: So that's just the energy you assume it has when you have pair production?

MICHAEL SHORT: That's right. So the electron and the positron annihilate, turning their mass into energy. Since the rest mass of each of those is 511 KeV, the photons come off at 511 KeV.

AUDIENCE: OK. Got it.

MICHAEL SHORT: Yep?

AUDIENCE: So when you say the electron and the positron annihilate, is the positron just a hole?

MICHAEL SHORT: Ah, good question. The positron is not a hole. So like here, we were talking about an electron hole pair. A hole would be, let's say, an atom with a missing electron. A positron is a particle itself of antimatter that has the same mass, but the opposite charge, as the electron. And so every particle's got its antimatter component, like there are antiprotons and antineutrons, that if they find their regular matter selves, do annihilate. Yeah?

AUDIENCE: If the detector doesn't pick up gamma rays directly, how do you measure-- like, why would a small detector see double escape?

MICHAEL SHORT: So a small detector would see double escape, because at first-- let's say a gamma ray interacts and undergoes pair production. And so it's going to, let's say, create an electron-positron pair. And it's going to give them a whole lot of extra energy. So they're going to knock around and ionize things. And that's going to count up to the energy of the gamma minus MeV. Then, when they annihilate, if it's a small detector chances are those gammas just get out.

We're going to be going over why soon, when we get into mass attenuation coefficients, or cross sections or interaction probabilities. But as the energy of a gamma goes up, it's interaction probability goes way down. And this is a fairly high energy photon, compared to, like, the easier KeV X-rays that you tend to see. So chances are, these photons get made from annihilation, but they don't stay in the detector.

Then the bigger the detector is, the more mass there is in the way, and more likely they get counted. But all of this happens, well, at the speed of light. At least the photon part. And so it's so fast that the detector picks it up as that sum of all the different processes of energy in one time interval. Like I said, this is the harder stuff, because it's not direct. It's a multi-step process

with different possibilities. But it's important to know where the single and double escape come from, where the 511s come from, which is outside the detector. Yes, have a question?

AUDIENCE: Yes. Would you say the detector can-- the detector itself can measure the energy of a photon? Is the measurement of 511 KeV, is that due to the fact that it will hit an electron and cause the-- what is it called?

MICHAEL SHORT: Like ionization cascade? Exactly. Yeah so if a 511 KeV photon enters the detector, the detector does not know until an electron interaction happens. So most of the photons that enter this detector leave the detector. That's why if you actually look at the banana stuff, which I'll pull up right now, at the efficiency, check out those values, there. Efficiency is in the realm of 10 to the minus 4 or 10 to the minus 3, which is to say that out of every 1,000 or 10,000 photons that enter the detector, one of them undergoes an electron interaction and the other 9,999 just goes screaming on through, and the detector does not know that they're there.

The way that Mike Ames got these efficiencies is by putting a source of known activity in, calculating how many gammas the detector should have picked up, and taking that divided by the number that it actually picked up. And so that way, you know how many gammas really went in, and how many gammas it saw. And that's how you get the detector efficiency. And you will have to account for this when you do this on the homework problem. So the only quantities you're going to need is how many gammas that you get, what's the efficiency, and then back that out.

So you'll have to calculate the activity of the bananas, and then figure out how much a banana weighs, and then you should be able to calculate the radioactivity of one banana in curies, or becquerels, or microcuries. It's all good. So good question. So it's three of, so I'm going to let you guys go. But I'll see you again tomorrow, and we'll review a little bit of this stuff. And we'll get into more of the math of the cross sections and why Compton scattering and pair production take up the energies that they do.