MICHAEL SHORT: Today we launch into radioactive decay. And so this is kind of what makes us, us in this field, right? Now that you've learned the general cu equation we're going to look at some very simple, specific cases, and specifically all the different things that can come flying out of nuclei and the orbiting electrons around them.

First I'd like to try and develop a generalized decay diagram. What are all the different ways that nuclei can decay? And I had written one of these up to show on the slides, and my one-year-old son fixed it with a bunch of markers and crayons, so I think we're going to have to redo this from scratch.

So let's say you had a generalized unstable nucleus over here. And we're going to start drawing a generalized decay diagram. You'll see decay diagrams, well, much like these. I've already shown you a couple of these, like these decay diagrams for uranium 235, soon as I clone my screen so you can see it. There are a couple of axes that aren't drawn on these decay diagrams that will help you interpret them.

And the first one, the imaginary y-axis, is in order of increasing energy. And the second imaginary y-axis is z, atomic number. So this will help you determine how we read these and how to actually write them. Now what are some of the different ways you've heard of things that can radioactively decay, or that you might have read from the reading? Just yell them out.

AUDIENCE: Alpha decay.

MICHAEL SHORT: Alpha decay. So in alpha decay, what actually happens? Let's say that we had a parent nucleus with atomic number z and mass number a. What does it change into? Anyone know what an alpha particle consists of? Yeah.

AUDIENCE: A helium nucleus.

MICHAEL SHORT: A helium nucleus. So let's just say helium. This will be a 4 and a 2. and there's going to be some daughter nucleus-- we don't know what-- with z minus 2 protons and a minus 4 total nucleons. So if we were to describe alpha decay on a decay diagram, where would we write the final state of this alpha decayed daughter nucleus? To the left or to the right? I know it's like 9:00 AM, but someone just shout it out. You don't have to raise your hand.

AUDIENCE: To the left.

MICHAEL SHORT: To the left. Yep. Something that's decreasing in z and also decreasing in energy, we would draw an alpha decay like this to the left. So let's say this would be something more stable with a z minus 2-- make that clear-- and an a minus 4. What are some other ways things can decay? I heard a whisper.

AUDIENCE: Beta.

MICHAEL SHORT: Beta decay. So what happens in-- usually by beta decay, we're referring to beta minus decay, which would be the emission of an electron from the nucleus. Again, what's the physical difference between a beta particle and an electron? Nothing. What's the nomenclature difference? The beta comes from the nucleus. Otherwise, when they come out, they're kind of indistinguishable. So what happens in beta decay? Let's say we have the same parent nucleus starting with z,a. We know it emits an electron with no mass. And what else? This is just a matter of conservation of things here.

AUDIENCE: Anti-neutrino.

MICHAEL SHORT: There is an anti-neutrino which has pretty close to no mass and no charge. And what about this daughter nucleus? How many protons and total nucleons would it have? Yeah.

AUDIENCE: Should have one more proton.

MICHAEL SHORT: Should have one more proton and how many more total nucleons? The same. Yep, like that. And so how would we draw beta decay on this generalized diagram, to the left or to the right?

AUDIENCE: Right.

MICHAEL SHORT: To the right. It's increasing in z. I haven't defined any scale, so let's just say that's a change of 0. That's 1. That's 2. And that's plus 1. That's plus 2. Hopefully we won't get to today. So a beta decay would proceed thusly. So you'd have some other stable nucleus with c plus 1 and mass number 8. What are some other decays you might have heard of before?

AUDIENCE: Electron capture.

MICHAEL SHORT: Electron capture. So in electron capture, what actually happens? Start with the same parent nucleus. In this case, the nucleus actually captures an electron from one of the inner orbitals. And so that, in effect, like, neutralizes a proton, right, in terms of charge. So what do we end up with?

Yep. So we'd have some daughter nucleus. If it neutralizes a proton, we'd have one fewer protons. And then how many total nucleons? The same. Yep. There we go. And so if we were to draw electron capture on this map, we would have one fewer proton. So we could have some sort of decay by electron capture. And anything else? What other particles can be emitted from a nucleus? Yeah.

AUDIENCE: Positrons?

MICHAEL SHORT: Positrons. So let's get this list going up. So if we start off with a parent, z and a, we know we emit a positron, which is the anti-matter equivalent of an electron. So same general characteristics except opposite charge. In this case, we'll give it a 0 protons and 0 neutrons. And we end up with-- well, the same daughter nucleus.

So we could say that this precedes by positron creation or electron capture. It's the same process, or the same ending state. But can you have positrons in any possible decay? We actually went over this once. Anyone remember? Yeah, so you're shaking your head no.

AUDIENCE: You have to have a certain energy, but I can't remember what the energy is.

MICHAEL SHORT: We'll get back into that. You're right. So I'll put a little box around this because you have to have a certain amount of energy in order to create the positron. And what else? What about the easiest one? What else can be emitted from a nucleus?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: I heard a couple of things. Neutrons. So certainly if you emit a neutron, there are some very unstable nuclei, like helium 5, which exists for what, 10 to the minus 26 seconds or something, that could omit a neutron. If we start off with z and a, then we'll start off with a neutron and a daughter with the same z and a minus 1 total.

So what would that look like on a decay chain? You don't usually see this, but we'll draw it anyway. It would go straight down, right? So there'll be some other nucleus. So it'd be the same z, but an a minus 1. And it could decay by neutron emission. Yeah, that totally happens. If you look at the very, very right edge of the table of nuclides-- let's go back to the home page for that-- and look at the super neutron rich. Like helium 10. Who's ever heard of this? Doesn't even say, let's say, two neutrons. So this is so unstable that it just immediately spits out two neutrons.

So yeah, these things happen. You won't tend to see this decay in textbooks because it only happens for exceptionally unstable nuclei. But yeah, that's true. It does happen. What else could happen? Remember we've been talking about-- yeah.

AUDIENCE: Gammas?

MICHAEL SHORT: Right. Could be gammas. And so I'll make one little extra piece here for gamma decay, which is nothing more than a photon emitted from the nucleus. We start off with a parent z and a. And this becomes-- well, what? Should I even write daughter nucleus? I see some people shaking their heads no. Why not? Yeah?

AUDIENCE: You have essentially the same atom. It's just one of its electrons should be at a lower energy state.

MICHAEL SHORT: Yep. Very close. You have the same atom, so let's say the same parent, with the same number of protons, the same number of total nucleons. And I'll just correct that to say one of its nuclei is at a lower energy state. But otherwise everything is completely correct.

So why don't we put a little star here to say that that was at an excited state? Just like electrons can be promoted to outer shells, pick up a little bit of energy, so can nucleons. So can protons and neutrons. And this is going to be a subject of, well, great discussion in 22.02. For now all you have to know is that nucleons, like electrons, can occupy higher energy states. And when they fall down to lower energy states, they can release that energy in the form of a gamma ray.

So you could also have, let's say, squiggly line gamma decay to something stable. And so this right here would be the generalized decay diagram. Anyone ever heard of one isotope that undergoes all these possible decay mechanisms? Glad no one's saying anything, because neither have I. There's one that comes close. Actually, if you look at-- no, that's not this part I want to show you. I want to show you the big one. If you look at potassium 40, the nuclide we probably talked about the most so far, it covers most of the space of this generalized decay diagram.

And there was a question that came through-- at least, I think for non-anonymous email, what is it that makes these even, even versus odd, odd nuclei less or more stable? Anytime you have an odd, odd nucleus, both the number of protons and the number of neutrons, these nuclear shells are not fully occupied and they're not that stable compared to an even, even nucleus that has an even number of z and an even number of n. Just kind of like electrons, these things tend to travel in pairs. And not fully occupied energy levels will be left stable.

Potassium 40 happens to be one of those odd, odd nuclei that is relatively unstable. And it can go either way. Either you can lose a proton or you can gain a proton by competing mechanisms like positron or electron capture or beta emission. So this one I like a lot because it gives you almost every possible decay with the exception of alpha decay and spontaneous neutron emission. It's not that unstable.

Then the only one really missing from here, I found what I think is the simplest decay diagram ever, dysprosium-151. There's only one thing it can do is it can decay by alpha decay to its ground state. I want to point out a few of the features of these decay diagrams so you know what to look for. Up here is the parent nucleus. Down there is the daughter nucleus. And these energies are not absolute. They're relative to the ground state of whatever the daughter nucleus is.

So simple example helps show you that gadolinium-147 doesn't have a binding energy of 0. This is relative to the ground state of gadolinium-147. And that will tell you that the Q value for this reaction is 4.1796 MeV. These things are usually listed in MeV unless said otherwise.

You also might notice a pattern that most alpha particles tend to come out around 4 MeV or larger. The answer to why is going to be given in 22.02. Yep.

AUDIENCE: Where do these percentages come from?

MICHAEL SHORT: These percentages tell you the probability that each decay will happen.

AUDIENCE: Oh, yeah. Like how do we derive-- how do we find those out?

MICHAEL SHORT: Ah, these are usually measured because it can be-- let's say things get quantum and difficult in terms of calculating these. And our knowledge of wave functions of, well, higher and higher a or z nuclei gets a little more tenuous. So a lot of these would be measured. You can look at the number of alpha particles of each energy that you observe, and then you get the average probabilities.

For this one, it's simple. There's 100% probability that this is the only thing that exists. The other things to note, the half life will be given up here, in this case, at 17.9 minutes. So relatively long half life compared to helium 5. And we'll be going over what half life is and what they are on Friday.

And then the last thing are the spin states of the initial and final nuclei, which we will not cover in this class, but you will cover in 22.02. So don't worry about those now, but do know that when you need to go find the spin states of the initial and final nuclei to see if certain transitions are allowed, this is where you're going to go.

Any questions on what you see here on how to read these decay diagrams? Cool. OK.

Then let's move on to the simplest of them, which, in the table, can look the most complicated. So here you can see that there's a whole bunch of different probabilities for different alpha decay nuclei. This is one of those more complex examples where the easiest thing to do is just measure, see how many alphas you get at each energy, and this will give you the approximate probabilities that each decay happens.

And you'll notice here that the final energy states for each of these alphas is not necessarily 0. This will tell you what they are relative to the ground state of, in this case, thorium 231. So you can emit an alpha from any combination of nuclear shell levels inside this nucleus. And you might end up with a new daughter nucleus whose protons or neutrons are in excited states. And the way you remove those excited states is gamma decay, like we talked about here.

So a lot of alpha decays are immediately followed by a chain of gamma decays, or what we call ITs, or isometric transitions. So you'll see a couple bits of notation. For example, gamma decay, you may hear it called isomeric transition. We'll try to give them all so that in the various readings you have, you know what's what.

So notice here, you can have, with a probability so small that they didn't bother to draw it, an alpha decay 2.634 MeV. And then any series of gammas from, let's say, from this state to that state, and then from this state to one of those or one of those, and then another one down there. So an alpha decay may be followed by a whole bunch of gamma transitions, or as few as none.

If you want to see what the alpha energies are, well, let's head to the table of nuclides and look at uranium 235. So if we look up U 235, you can see that it alpha decays to thorium 231. And I'll show you the part of the table that I didn't show you in the slides, which is then you've got a table of alpha decay energies as well as relative intensities and what's called a hindrance.

This stuff right here comes from the fact that different alpha decay energies can happen with different probabilities at different times. So the half life of a particular alpha decay can be slightly different. And this is another one of those really kooky things, where certain energy alpha transitions will happen a little more often initially then finally. But we don't have to worry about that yet. I just want you to know that's why the hindrance is there.

And so you can look, from this table, what's the probability that each of these alphas will come out. And there's going to be some uncertainty associated with these. This is going to usually be some sort of measurement uncertainty. Then you might also ask, why is it that the highest energy alpha ray is not the same energy as the Q value? So for this, it's a greatly simplified application of the Q equation that we learned last time.

So for here, what are the two equations that we need to conserve if we have a system consisting of-- we have our initial nuclei going into our final nuclei. And they go off in equal and opposite directions. If it's alpha decay, then we have no little initial nucleus.

We just had a large initial nucleus at rest. And afterwards, you've got a small final nucleus, which we know is the alpha particle, and a large final nucleus, which we'll call the daughter product. And let's say this is the parent. It's a much, much simpler system than the general one we analyzed last week.

So what are the equations that we'll use to serve to find out what's the energy of this alpha particle? Anyone? Same three answers as always. Yep.

AUDIENCE: Mass, energy, and momentum.

MICHAEL SHORT: Yep. Mass, energy, and momentum. I'm going to lump these two together because they're kind of the same thing. So let's just go with energy and momentum. So what is the initial kinetic energy, or let's say, the initial kinetic energy of this parent nucleus we can assume to be 0. What about the final kinetic energy of the system?

Well, there's only two particles. There's going to be some kinetic energy of the alpha particle plus the recoil kinetic energy because if the alpha goes in one direction, the daughter nucleus has to go off in the other direction. And the total energy comes out to Q.

This Q value you can get by conserving mass, where we can say that the mass of the parent has to equal the mass of the alpha plus the mass of the daughter plus Q. So that's where we can get Q if we don't know it already. Luckily, we know it already. So there we've used mass. There we've used energy. And now what are the momenta of the initial and final states here? Anyone? Just shout it out. What's the initial momentum of the parent nucleus?

AUDIENCE: 0.

MICHAEL SHORT: 0 equals-- what's the momentum of the alpha? Anyone remember that trick if we want to say p equals mv equals what more convenient form that contains the energy? Square root of 2 mt. So let's go with that. So there'll be the square root of 2 mass of the alpha, kinetic energy of the alpha, minus the square root of 2 times the mass of the daughter times the kinetic energy of the daughter because these have to have equal and opposite momenta.

So all we have to do is move that one over here. This makes that equation easy. Everything's got a square root of 2. We can square both sides. And we end up with a pretty simple relation, mass of the alpha times the kinetic energy of the alpha is the mass of the daughter times the kinetic energy of the daughter.

We don't usually care about the kinetic energy of the recoil nucleus or the daughter because the range is so small that we usually don't get to measure it. But we are trying to measure what are the actual alpha particle energies so that we can reconstruct this table down here.

So we can take our energy conservation equation and rearrange it to isolate td, the kinetic energy of the daughter, and say td equals Q minus t alpha. Substitute that in here. And let's rewrite what we've got. Mass of the alpha, t alpha, equals mass of the daughter times Q minus t alpha. If we multiply each term in here by md, we get mdQ minus md t alpha. Then we can take all of the t alphas on one side. So we'll just add md t alpha to each side.

So we have m alpha t alpha plus md t alpha equals md Q. We can factor out the t alpha here. And then we can divide each side by m alpha plus m daughter. Cancel out the ma plus md. And there we have the answer. The kinetic energy of the alpha is just the q value times the ratio of the daughter mass to the total mass.

This should look awfully familiar. When we did this in the frame of neutron elastic scattering or any other reaction, we had the same equation with just different notation. So do you guys recognize this firm, where we had t3 equals Q times m4 over m3 plus m4. It's the exact same result, just different notation. Last time we did it in the most complex way possible. This time we started off with the simplest possible equations for alpha decay. In the end it's the same Q equation. We just didn't bother with all the other terms and angles and things that we don't need.

So is everyone clear where this came from? Cool. And that's why you're never going to see an alpha particle that's got the same energy as the initial minus the final energy because the recoil nucleus, or the daughter nucleus, takes away some of that kinetic energy in order to conserve the momentum of the system that was initially at rest.

Another way to say this, for those who like center of mass coordinates, is the center of mass of this system was just the parent nucleus. It was at rest. The center of mass of the final system has to remain at rest to conserve momentum. But again, I won't go much into center of mass because I find it a little unintuitive. I'll stick with a laboratory frame of reference.

So any questions before I move on? Alpha, I think, is the simplest case of radioactive decay. And I think now you know all you need to know about it. Yes.

AUDIENCE: So why do you get so many different types if we just calculated it? Like mb, in mass [INAUDIBLE] change?

MICHAEL SHORT: Not ma and md. But ta and td would change. Yep. So in this case, for different alpha decays, they'll have different Q values. So the Q value of, let's say, this top alpha decay is this energy here, 4.676 MeV minus 0.634. So use a different Q and you'll get different ta's and td's. So don't worry. You'll get chances to try out these calculations on the homework, where I'll actually ask you to calculate some of these from this equation, make sure you get the same values as the table.

Any other questions on alpha decay before moving on to beta? Just going in order of the Greek alphabet.

So beta decay is a kind of funny one. You don't tend to get a beta particle out at the energy of this Q value. You actually end up getting a spectrum. And this measured spectrum of different beta kinetic energies is what led to the thoughts that there must be something else carrying away some of that extra mass or some of that extra energy. I say that like it's the same thing because it totally is.

And this is what led to the thinking that there's got to be some other very difficult to detect particle. So the theorists here we're saying, if we know the initial and final energies from beta decay, and we know that we get a spectrum of different beta energies and the probability of finding a beta particle at energy Q drops to, like, 0, you'll almost never see it. There's got to be something else carrying away the energy.

So this idea of the neutrino, or in this case, the anti-neutrino, was proposed a long time before it was confirmed. And finally we know why. And one of the questions I want you to think about, because it might be on an exam in exactly two weeks, is if this is the relative number of electrons from beta decay as a function of energy, what does the number of anti-neutrinos versus energy look like in order to maintain conservation of energy? So it's something I want you guys to think about, but I'm not going to tell you what it is until the solutions for an exam.

In the meantime, another thing to note is that these beta decays can also be followed by any number of gamma transitions. I've given you a simple one. If you want to look up simple ones to test your knowledge, go with the light elements. They don't have that many nucleons and they won't have that many transitions.

For example, if we pick a beta decay nucleus, something simple. Let's go with lithium, which typically has-- the stable isotopes are lithium 6 or lithium 7. So do you think that higher or lower mass number lithium will tend to go by beta decay based on this generalized decay diagram? It's what?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Lower. Lower proton number? Well, we've got to stick with the number of protons because we need to remain lithium. So in other words, do you expect lithium 4 and lithium 5 or lithium 8 and lithium 9 to go by beta decay?

AUDIENCE: The higher ones.

MICHAEL SHORT: The higher ones. OK. If you guys remember the mass parabolas from a couple of weeks ago, we delineated where you'd expect beta decay in order to increase the proton number. So if you've got too many neutrons and not enough protons, chances are beta decay will help equalize you out.

So as a guess-- I haven't even tried this at home. Let's see. Let's see what happens with lithium 8. Oh, look at that. Beta decay. It can also decay by beta plus 2 alpha, which is another word for the nucleus just blows apart. It's interesting, too, if you read Chadwick's paper again, the way he described a beryllium nucleus is consisting of a neutron plus two alpha particles. Interesting, huh? Lithium 9 could decay by--or let's say lithium 8. What do we have? Beta plus 2 alpha. Yeah.

So Chadwick described any nucleus as consisting of these elementary-ish particles that you could measure. And in this case, you kind of see a physical example. When this nucleus blows apart, it just becomes two alphas in a beta. Interesting. But let's look at the beta decay to beryllium 8. Pretty simple.

You may ask why can't you have beta decay directly from the highest energy to the ground state energy? That is a 22.02 question that I'll mention. There are allowed and unaligned transitions between spins and energy states. So if you're wondering why isn't every line drawn, in the case of really complex nuclei, there aren't enough pixels on the screen sometimes. But for the simple nuclei, there are actually rules of selection to decide when you can make this transition.

But a lot of beta decays will usually be something like a beta decay followed by a gamma. So let's see a couple of well-known examples. For example, carbon-14. This is the basis behind carbon dating, one of those rare instances when you have a beta decay directly to the ground state. It's about as simple as it gets. And because the half life is 5,730 years, it's really useful for dating when did an organism or piece of material die on the timescale of, let's say, tens to tens of thousands of years.

Once you've gone past a few half lives and there's very little carbon-14 left, there aren't a lot of decays left and your counting statistics get crappy, and it gets harder and harder to carbon date things. The basis behind this is that all living organisms that are intaking and exhaling carbon by some means remain in isotopic equilibrium with the carbon surrounding them.

And while most carbon is CO2, and food and whatever is carbon-12, you're going to have a little bit of carbon-14 production from the upper atmosphere. This is usually a cosmic ray phenomenon, which we'll get into when we get into cosmic rays.

The moment you die you stop intaking carbon, and the little bit of carbon-14 in the cloth and the food and your body, whatever, starts to decay naturally with a very regular decay curve. And so this is the whole basis behind carbon dating. And in the next p-set, you'll actually see how this was used to debunk the Shroud of Turin, or the supposed burial cloth of Jesus of Nazareth, because the carbon dating data just didn't check out. As much as people really wanted to feel like we found it, no. Science. That's the answer. No.

Another well-known one we've talked about before is molybdenum 99 decaying to technetium 99 meta stable. Notice how here, any number of beta decays and any cascade of very fast gamma transitions, they almost all end right here at this state of about-- let's see, there's two numbers written over each other. But it's about 140 keV or 0.14 MeV.

This transition from this state to the ground state is a slow transition. So you can actually build up technitum 99 in what's called series decay, which we're going to cover on Friday. And then you can use these 140 KeV gamma rays to do medical imaging. So when you get a medical imaging procedure done, chances are this is how it's done. You get moly 99 out of a reactor or an accelerator, chemically isolate the technetium 99 meta stable, which lasts on the order of six days or so, very quickly get it to someone, inject it, and image where do the gamma rays go, or where do the gamma rays come from?

One last notable one is responsible for a lot of, well, problems when folks go urban exploring in old dentist's offices. Nowadays they have electrostatic x-ray machines at dentist's offices. But back in the day, you could get a little button of cobalt 60, which would emit two very characteristic gamma rays in addition to its beta decays. So normally what happens is cobalt 60 decays quickly to an excited state and gives off two gamma rays in succession, which would be used for imaging.

Problem is that's the a cobalt source. And if you don't know what it is, and you're like, oh, cool, what's this blue thing, I think I'll put it in my pocket and keep it-- that has been responsible for some injuries from some folks that didn't know any better.

And then how do you detect the neutrinos? We talked about the theoretical reason why they exist. Let's actually see how they're measured. There is a hollowed out salt mine of some sort called Kamiokande in Japan. It's a humongous hole in the ground filled with water, for a reason, and lined with tens of thousands of highly sensitive photo tubes that can pick up tiny, tiny amounts of light.

The reason for this is because neutrinos, as you saw in problem set 1, are always traveling near the speed of light in a vacuum. So if the speed of light in a vacuum, let's call that 1, and the velocity of the neutrino-- wasn't it something like 9. 999c or something like that? It was pretty high.

The speed of light and water is significantly less than the speed of light in a vacuum. When you have a material or a particle that goes faster than the speed of light in the medium that it's traveling in, then you can produce what's called Cherenkov radiation, which I think I've mentioned once before. It's kind of like a sonic boom in that you get a conical shockwave of energy radiated from that particle that tells you which direction it's coming from. But instead of a sound wave, you get light.

And this whole detector is designed to look at the ellipses of Cherenkov radiation released by neutrinos and anti-neutrinos. So what happens is if a neutrino happens to interact with the water here, it produces Cherenkov radiation lighting up a ring of these detectors so you can tell it's energy and you can tell where it came from. So if you, let's say, can correlate a supernova or some sort of crazy galactic whatever with a slight burst of neutrinos, then you've got a pretty significant astronomical event.

It also led to my favorite BBC headline ever, "Particle physics telescope explodes." You'd see this on, like, Fox News or something. No, this was the BBC. What happened here is one of these 30,000 or so tubes was slightly defective, couldn't hold the pressure, and it burst. And the resulting sound shock wave from one photo tube bursting blew up about 11,000 of them.

So yeah, the particle physics telescope kind of did explode. They did rebuild it and it's still going. It was an expensive repair because all 11,300 something tubes had to be rebuilt. And if you notice, there's a guy on a boat there. How do you install them? Well, you float on a boat quietly, and put the photo tubes in, and raise the water level, and float to another part of the detector quietly, and continue installing the photo tubes until you're done.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Yeah. You don't. Yeah. Don't sneeze. So yeah. Favorite BBC headline ever. Thanks again, science.

For positron decay-- OK, we've got about 10 minutes left-- for positron decay, this is the energy that you need in order to make a positron. It is approximately exactly double the [INAUDIBLE] rest mass of an electron. And the question usually comes up, well, a positron has a rest mass energy of 0.511 MeV. Why do you need double that to make the positron? Because in order to conserve the charge of the system, you have to shed an orbital electron.

So the system has got to be able to lose two electrons in the process, one positively charged and one negatively charged. And so that's why the Q for positron decay is just going to be-- remember, this symbol's the excess mass here, excess mass of the parent minus excess mass of the daughter minus 2 times the rest mass of the electron squared.

To refresh your memories a bit, find some empty space. The excess mass is nothing more than the mass minus the horrible approximation of the mass. So the excess mass and the real mass are directly related. And these are things that you can look up. Just to remind you guys that excess mass and mass and binding energy and kinetic energy are all related, again, by the Q equation. It's probably the last time I'll say it because I think that's about 100, by my count.

Positrons can be used for some pretty awesome things. And in the last five minutes or so, I want to show you some work done by Professor Brian Wirth at the University of Tennessee, Knoxville on positron annihilation spectroscopy, using anti-matter to probe matter and find out what sort of defects exist. And as a nuclear material scientist, I'd be, well, terrible if I didn't inject a little bit of materials and how we use nuclear stuff in 22.01 in order to probe that thing.

So the way that positron annihilation spectroscopy works is that, well, matter's mostly empty space. And then in a regular crystal lattice, where the atoms are arranged in a very regular array, let's say these atoms have their orbital electrons. The empty space between is also arranged in a very regular array. And positrons annihilate with electrons to produce-- well, we'll find out in a second. But where in matter would they want to live, or where would they last longer? Not near an atom, but near the space in between.

So you can map out the empty spaces in matter in a regular crystal and calculate an average positron lifetime. If you were to fire a positron into this matter, how long would it sit and bounce around before colliding with an electron and releasing that extra rest mass energy? It turns out if you have crystalline defects, the positrons tend to last a little longer. There's a little more empty space, which is to say there are more places with a slightly less probability of finding an electron. And so they last longer.

And you can measure the lifetime of positrons before they enter the material, and then how long before they produce their characteristic destruction gamma rays. So if you think about it, you have a positron coming in with a rest mass 0.511 MeV. And it collides with an electron from some orbital nucleus that has the same rest mass. The positron and the electron annihilate sending off gamma rays in opposite directions, where the energy of this gamma is same thing, 0.511 MV.

So you can tell when a positron was destroyed because you instantly get 1/2 a MeV gamma ray. Or actually, you get two 1/2 MeV gamma rays. Then the question is, how do you tell its lifetime? Let's go back to something that I didn't quite point out, but I want to show you now, is this positron decay is immediately followed by a 1.27 MeV gamma ray, which in PAS, or Positron Annihilation Spectroscopy, we call this the birth gamma ray. This gamma ray is emitted the instant this nucleus is born. And the positron takes a little bit of time to get destroyed.

So you actually look at the difference in time between sensing the 1.27 MeV gamma ray and the 0.511 MeV annihilation photons. And that is measured in, let's say, hundreds of pico seconds with resolution of around 5 picoseconds. And you can then tell, from the lifetime and how many survive, what sort of atomic defects might exist in the material.

So if you want to count the number of missing atoms or vacancies in a material, which is extremely important to those of us in radiation damage, you can do so with positron annihilation spectroscopy.

So I think I wanted to show you a little bit about how this works. You start off by making a radioactive salt sandwich. You take some sodium chloride, specifically of the isotope sodium 22, which is giving off positrons all the time. And you sandwich that radioactive jelly between the two slices of bread, better known as your sample. That way you catch every positron that gets out so you don't lose half of them to one side.

You've got two detectors on either side waiting. So there's some probability that the photons emitted are going to go in the direction of the detector. So you miss most of the signal, but so what? Whenever you actually sense a 1.27 MeV gamma ray followed by two 511 KeVs here, then you know you've had a positron annihilation event, and you can actually count the time between when those things happened. And you can see the number of counts and get the average positron lifetime from finding out how many counts you get every five pico seconds, for example.

There's something to note about these counting spectra. Anybody know why they're so smooth up here and then they're so delineated down here? Anyone have an idea? You're going to see this a lot in 22.09, when you actually count theta particles or alpha particles and your counting statistics get a little crappier. This is a log scale of counts, or in this case, counts per five pico seconds. 10 to the 0's better known as 1.

So you're looking at one count or two or three. You're looking at the discrete event. You can't have one and 1/2 counts. So you're going to see this kind of thing quite a lot when you're trying to count very rare events. And if you're down in the weeds like this, let's just say your statistics aren't that good. But since this is a logarithmic scale, 10 to the 4th is better known as 10,000, that's enough to get good statistics and fit a nice curve to this positron lifetime thing.

This is what one of them actually looks like. And you can kind of tell. Inside there is where all the positrons are coming out. So that's probably lead shielding. Here's two detectors on either side. And here's another detector to detect that 1.27 MeV birth gamma ray. So if you get those three events happening all at the right time, you've got a positive event that you can count.

And last thing I'll mention is you can actually use this, like I said, to gut not just the number of vacancies, but the number of different size defects. You might have two or three missing atoms next to each other, which will have different positron lifetimes. And you can actually count the number of each of these to get the diameter or the size of these atomic defects.

And this is one of the ways of confirming our models of radiation damage, which is, like, all I do. That's half of our group. If you want to read anything more about positron annihilation spectroscopy, all the stuff in these slides were from these references, which you can look up easily on the MIT libraries. We have access to everything because that's MIT. We just buy everything there is. So I'd encourage you to look here if you want to see more details on how this works and why it works.

So because it's exactly five of five of, I want to open it up to any questions on alpha decay, beta decay, positron decay, or the decay diagrams that we've developed today. Yes.

AUDIENCE: What is the most dangerous kind of decay?

MICHAEL SHORT: What is the most dangerous kind of decay to be exposed to? So in this case, you'd want to say the energy of the particle is held constant, and the number of those particles is held constant.

And actually, we're going to answer this question when we get to medical and biological effects. But let's do a little flash word now.

Let's assume, if you want to see which one of these decays is most dangerous, we'll have to say constant-- constant-- energy of decay, constant activity, and what else can we hold constant? Well, constant you. Let's say the same number of particles end up hitting you.

That depends on whether they're inside or outside your body. If you were to ingest material, then alphas would be your worst because alpha particles are massive and charged nuclei, which means they interact very strongly with matter around them. So if you ingest them and they end up incorporating into your cells, where they can just get next to DNA, they can just blast it apart.

However, an alpha source of equal strength held in your hand would do nothing. The dead skin cells are enough to stop alpha particles. And we're going to find out exactly why when we look at the range and stopping power of different particles and matter. From the outside, alphas won't really get through your skin. Betas might get through a little bit of your skin, but not much. Gamma rays will mostly go right through you.

It's neutrons that are the real killers. Those neutrons are heavy but uncharged. So they interact kind of strongly. When they do hit, they pack a wallop and they do a lot of damage. And they're mean free path, and you is on the order of 10 centimeters. So a neutron source from the outside can do a lot of damage from the outside.

The alphas and the betas would be stopped by your skin and clothes. The gamma rays, almost all of them will go right through you. And you guys will actually have to do this calculation to find out how many gamma rays would you absorb from a gamma ray emission, and how many go right through you. The hint is most of them get out.

So there's an exam question we used to ask in 22.01 that I was asked during the first exam, is you've got four cookies, an alpha emitter, a beta emitter, a gamma emitter, and a neutron emitter of constant energy and activity. You must do one of the following. You have to hold one in your hand at arm's length. You have to put one in your pocket. You have to eat one, and you have to give one to a friend. What do you do and why? Anyone have an idea?

Pop quiz. Yeah?

AUDIENCE: Probably give the neutron one to a friend.

MICHAEL SHORT: That's right. I can tell this is the west, because when I asked a group of Singaporean students the same question, they would eat the neutron to save the friend because of Confucian ethics. Yeah, it doesn't fly here. Your answer is correct because this is America. What would you do with the other three?

AUDIENCE: Eat the gamma.

MICHAEL SHORT: Eat the gamma because most of the gammas will just get to the friend, right? What about the alpha and the beta?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Yeah. Hold the beta at arm's length because there's another aspect of shielding betas that we'll get into. When betas stop in material, they produce some low energy x-rays called bremsstrahlung. So you'd want to get those far from you. And the alpha in your pocket will just be absorbed by the pocket. Yeah, so that's the right question. So you're not going to see that on the exam. But good news is you pretty much got the right answer because this is America.

Probably time for one more question if anyone has one. Cool. If not, then I want to remind you Amelia will see you on Thursday, so do come to class Thursday. I'm going to change the syllabus to reflect that. And we'll have two hours of class on Friday to get through decay and activity and half life, followed by an hour of recitation.

So I will see you guys Friday, and we'll see what mood I'm in depending on how the nano calorimetry goes. Could be a fun measurement.