MICHAEL SHORT: All right, guys. Welcome to the last official day of 22.01. Can't believe we've actually made it here. And you guys have learned a ton about how ionizing radiation does and doesn't affect different types of matter. If you've noticed that the whole class has been kind of taking a slant towards looking at issues in the public sphere from things like hormesis to dose, to risk, to power plants, today we're going to talk about food irradiation. One of the main reasons that we have all sorts of incredibly safe food today thanks to ionizing radiation, a lot of the myths and misconceptions and science behind what does and what doesn't happen when you irradiate food.

And you guys are fully equipped to determine not just is food irradiation safe, but how should it be conducted? How should it not be conducted and what would the effects really be? And with stuff that we did the last few classes, actually looking up research papers and discerning which sources are real and which ones are, let's just say, not, for lack of a bunch of four letter words, you can tell for yourselves what sources are actually worth looking at.

So just quickly go over the basics of food irradiation and maybe five minutes before we hit the primary sources. So the general idea here for anyone that got into the reading, which I'll pull up right here, is that we irradiate food to do a whole bunch of different things. Can anyone tell me, what are some of the reasons one might irradiate food?

AUDIENCE: Bacteria like E. coli

MICHAEL SHORT: Yeah, gets rid of bacteria, other harmful organisms. It just kills other organisms. Like what? Like bacteria. Anyone else?

AUDIENCE: Bugs.

MICHAEL SHORT: Yes, insects. It's actually used to either kill or sterilize insects so that they don't breathe and let's say-- oh yeah, totally, because the dose required to sterilize something is usually a lot lower than the dose required to kill something. Why do you guys think that is? Yeah?

AUDIENCE: To sterilize [INAUDIBLE] all you have to do is kill off your reproductive cells.

MICHAEL SHORT: That's right. And anyone remember what those quality factors look like for those reproductive cells?

AUDIENCE: Much higher.

MICHAEL SHORT: That's right. Let me bring it up. Let me go into the dose dosimetry and background. I think it'll help to actually see the numbers here. Let's go to the tissue quality factors. There we go. Right at the top of the list, reproductive organs. So it takes a whole lot less dose to sterilize something like insects or other bacteria or things, or I don't know if you can say sterilize viruses. It's still kind of under debate whether viruses are technically alive. They're right on that edge of what people would consider alive or not. And there's still a debate going on about what does alive really mean.

Yeah. You can sterilize the insect population. For example, who here's bought a bag of rice before, and who here has found some little rice bugs in that bag of rice before? Are you serious? I must shop at cheap store, I find them all the time. But the nice thing is if you irradiate them then they won't breed and continue to eat and breed in the bag and then you open the bag and you've got a swarm of, I don't know what those things are, rice weevils or something. I think I remember looking them up once because I was like what is this thing in the rice? Yeah, it's gross. But that's why we do food irradiation. Now, what else? What other reasons might want to irradiate food other than to kill or sterilize things in it? Yeah?

AUDIENCE: Doesn't it preserve like shelf lifes?

MICHAEL SHORT: It does preserve shelf life, especially of things like fresh fruits, vegetables, seeds, legumes. Anyone have any idea why? Yeah?

AUDIENCE: Well, it seemed like that would be just because it kills things that eat it.

MICHAEL SHORT: Yep. One would be it kills things that eat it, but the other thing is those plants have reproductive cells as well. Let's pick a good example. Anyone ever had really well sprouted bean sprouts before? Like not the fresh ones, but the really old ones? Not old like they've sat behind the fridge or something. OK.

AUDIENCE: Like super sprouted?

MICHAEL SHORT: Yeah, super crazy sprouted.

AUDIENCE: The super crazy sprouted.

MICHAEL SHORT: Anyone remember what they taste like? They are kind of bitter and rather unpleasant. So one of the main reasons for irradiating food is to prevent sprouting and prevent germination because as soon as the plant sprouts and starts to say like, all right, let's grow, starts to consume its store of sugars, water, nutrients and everything else and start generating other flavors, which tend to be fairly off flavors.

So another way that you can keep things tasting good, even if they don't have bugs or weevils or insects or viruses in them, is prevent them from changing at all through their normal metabolic processes. So it kind of freezes the food in place. Well, since I mentioned freezing, there's another little caveat to that. At what temperature do you think would be the best temperature to irradiate food?

AUDIENCE: Cold temperatures.

MICHAEL SHORT: You say cold, and why do you say so?

AUDIENCE: When you did that one thing, the temperature'd grow.

MICHAEL SHORT: Yeah, let's bring it up. We talked about G-values and temperature, and I think it's a little further in. It's in the chemical effects. So I'll jog your guy's memory a bit from just a week ago where we were talking about G-values or the number of different radiolytic byproducts of radiolysis byproducts that are formed as a function of temperature.

I'm not going to full screen that because that's going to get all freaky. But you can see that there's a whole lot more of them formed as a function of temperature. What's not shown here is what happens when this reaches 0 degrees Celsius? What happens to water at 0 degrees Celsius? Just look outside, what do we got? It freezes, OK. All these G-values are calculated assuming the free species are diffusing in liquid water.

When you freeze the food, you pretty much shut down diffusion. When you shut down diffusion, do these chemicals react or not in a different way? Can they move to find each other? No, they're frozen in place. You're stuck at the diffusion coefficient in ice, which is a whole lot slower than in free flowing water.

So in this way, you can kill whatever organisms are there even if they can survive freezing by directly damaging their DNA, without altering as many of the foods normal tastes, flavors, colors, whatever. And speaking of taste flavors colors, I want to bring up some of the pseudoscience. It didn't take long to find a couple of things on the internet talking about how we shouldn't eat irradiated food. And to that I say, well next time you spend five weeks straight on the toilet you may be thankful for food irradiation.

So let's look to see what sort of things could or couldn't happen with food irradiation based on random internet article. Again, not a useful source, but let's see what they say. Damages food by breaking up molecules and creating free radicals. That's true. What's the question we should be asking though is not does it damage molecules? But what do you think? Yeah?

AUDIENCE: Do the damaged molecules have any effect?

MICHAEL SHORT: Yeah. So one, do the damaged molecules have any effect? Were those same damaged molecules there to begin with? And the other question I want to ask is how much? How much is always the question you want to come back with when somebody says isn't it true that radiation does binary effect? Causes cancer, kills babies, whatever you want? Sure, enough. But the question is how much?

So there's a second source top 10 reasons for opposing food irradiation. Let's go through these a little bit one by one and look at some of the references, which they're not all bad. So let's see. In legalizing food irradiation we did not determine a level which food can be exposed and still be safe for human consumption.

So let's think about what that actually means. We never hit that LD 50 or LD 10 or whatever dose we found that will cause ill effects in humans. I would argue this is a good thing. If we haven't had any documented cases of people getting sick from food irradiation and we already get the effects that we want like stopping germination, sprouting, killing bad things, then great, let's not go higher. Mission accomplished.

Let's look at the references again. Reference one, they actually give a US code of federal regulations. Reference two, I dare you to find what they were talking about. Various filings over a period of 17 years.

AUDIENCE: Isn't that dating publication Federal Register?

MICHAEL SHORT: I'm not sure. I think it might be something more legit, but there may also be a publication called the Federal Register. I doubt the Federal Register publication has what's called filings, but these would be more official filings. But yeah, they're somewhere in the archives of somewhere. But at any rate--

AUDIENCE: [INAUDIBLE] from class.

MICHAEL SHORT: Again, I would argue that this is actually a good thing. We don't know to what level food irradiation can harm people. Now, let's think about some of the ways in which if done incorrectly it could harm people. Without me telling you ahead of time-- and this we'll see who did a little bit of the reading. --what sort of types of radiation do we use to irradiate food, and why? We have our choice of alphas, betas, positrons, gammas, neutrons, heavy ions, et cetera. What would you use, and why? Yeah?

AUDIENCE: Presumably ionizing so you don't have to activate any of the things [INAUDIBLE].

MICHAEL SHORT: So you said presumably ionizing.

AUDIENCE: Yeah, so you don't activate them and you get radioactive thiamine.

MICHAEL SHORT: OK. Which of these types of radiation are ionizing?

AUDIENCE: Sulphur, [INAUDIBLE], gamma.

MICHAEL SHORT: What do you mean by ionizing?

AUDIENCE: So they can lead to ionizations in the material.

MICHAEL SHORT: Oh. I would argue that every one of these types of radiation can ionize. As we've seen, they can all knock out electrons or other nuclei. But you're getting at an important point. Can anyone help Alex clarify? because you're getting onto the right track. Anyone? Yeah?

AUDIENCE: [INAUDIBLE].

MICHAEL SHORT: OK. So you may not want to use heavy ions or alphas because you don't want to plant anything in the material. Are you worried about implanting helium? What about iron? I mean let's say you want to use carbon ions and the food is Carboniferous. That's OK. But what about some of these types of radiation are quite different from the others when we were talking about everything from gamma to charged particle to neutron interactions? What sort of things might we look at as criteria to determine whether or not we want to use this for food irradiation? Stopping power. So stopping power, which is related directly to range.

So let's pick an energy of around 1 MeV. How do you find the range of 1 MeV alphas in food? Great. That's what I was going to say too. You can either do the calculations, or like most of us actually do, we just run a quick simulation that integrates all those calculations. So let's do that right now.

So we will take one MeV helium or 1,000k EV helium. We will approximate food as water with a stoichiometry of 2 to 1, a density of 1 gram per cubic centimeter, and let's allow for-- I think I already know what the answer is going to be. --10 microns. What are we getting for a range? 5, 6 microns for alpha particles in water. How well would alpha particles sterilize food? Not.

So let's say you have a chicken with diameter around 40 centimeters. The alpha particles would penetrate the chicken to a depth of approximately 6 microns. So alpha particles are probably out. What else is out based on range alone? Heavy ions.

How far do you think ion ions would penetrate into a chicken? Not far at all. Let's find out. Iron ions, I'm going to shrink the scale to 1 micron. We actually kind of did this on the homework, didn't we? I had you guys look at the range of lighter and heavier ions. What I'm hoping is that you'll have some sort of an intuition for how far ions tend to go in material. So as you go heavier, does the range go up or down? Range goes down.

As we expect we're getting just about 2 microns of chicken with heavy iron ions. So what could you do to get those to penetrate farther? Yeah, so you could boost the energy. So if you were to boost the energy of the alphas-- let's see. First of all, with our typical range relation where a range is roughly proportional to kinetic energy squared, how much more energy would we have to impart to the alphas in order to get them to the center of the chicken? Well let's try and work it out.

The range was about 6 microns and an energy of 1 MeV and we want to get to about 20 centimeters. Let's call that 6 centimeters. We're just going to use this approximation for now. And if we want to go from 6 microns to 6 centimeters, that is four orders of magnitude. So how many orders of magnitude would we need to increase the energy of the alphas to get through? OK. So we'd have to go to, let's say, 100 MeV you said.

Let's find out. We can just check this. So we'll switch back to alphas at 100 MeV. This is already looking to be fairly uneconomical. But this is physics, so let's find out. OK. So we're at about 1.5 centimeters. And that's again because at high energies this range relation changes to about proportional to t for really high energies. So we know we're going to have to get to around a GeV alphas in order to food irradiate chicken. That sounds really expensive.

Yeah. The proton cyclotron and MGH is about 250 MeV, and we're talking an eight or nine figure installation. Not worth it to irradiate food. What else might go wrong with GeV alpha particles? What may you induce? Yeah?

AUDIENCE: Bremsstrahlung radiation.

MICHAEL SHORT: Lot of Bremsstrahlung radiation. We pretty much ignored Bremsstrahlung of things like alpha particles and protons. But once you get into the GeV or tera electron volt range, you are going to get a lot of Bremsstrahlung and shielding those x-rays is going to be a mess. OK. So let's say we've excluded alphas and ions for the purposes of physics and we are left with batas, positrons, gamma and neutrons. What next?

AUDIENCE: Neutrons are also expensive.

MICHAEL SHORT: Neutrons are expensive. You either need a reactor, a spallation source, or a little pulsed fusion device, two of which we have down the street. Let's say you had a cheap source of neutrons. One of those, if you build it and there's money to be made then they will-- no. If there's money to be made they will build it, and if you build it, they will come with their chickens for irradiation. Why else physically would you not want to use neutrons to irradiate food?

AUDIENCE: They damage everything.

MICHAEL SHORT: They damage everything. That's OK, right? If they're damaging living organisms more than the food itself, that's OK. But what do neutrons tend to do when they interact with matter? And that's as specific as I can make the question so far. The correct answer is everything. Like what? Chris?

AUDIENCE: Well, like Alex said, they could activate-- [AUDIO OUT]

MICHAEL SHORT: Yes. So that's when I said you're getting on the right track. So thanks you guys for doing a team tag answer. Yes, they can activate things at pretty much any energy.

For this I'm going to jump to Janis. Like I said, I like to do things live, so show you guys that we could do it on the fly and respond to your comments in real time. It is showing, good. OK.

Though this is a skill I want to make sure that by the end of this class, which is about 35 minutes from now, you guys will know to jump to Janis and start looking for the right cross-sections because you're going to need it for the rest of your life career time at MIT. Pick probably two out of the three if you guys are going to be nuclear somethings.

I'm definitely in a different database right now. I was in incident proton data for other things that will become apparent soon. Let's go back to incident neutron data. We'll use the same database that we've been using all the time, the ENDF most recent database. Look at the cross-sections and let's assume you had some iron in your food. You are irradiating red meat. Nickel, copper, iron. Pretty common isotope of iron could be iron 58.

Let's now go down and find the z gamma the neutron capture cross-section for iron 58. It's decidedly non-zero at all energies, which means you're going to make iron 59. What happens when you make iron 59? I don't expect you to know, but where do we go to get the answer? Wall, yep, Tyree, that wall, the table of nuclides, whatever you want, or the Brookhaven table, whatever you want. The point is the table of nuclides.

Let's take a look at iron 59 and see what it does. It is not stable. It has a half life of greater than 10 days. It's a beta emitter and it beta decays to cobalt 59, which is a stable isotope. So you would be creating an unjustable source of beta particles. Nasty stuff. Let's see what those beta particles would do. They have about a 1.5 MeV energy. Let's look at the decay diagram. There are a few transitions, the most likely of which would give a beta and a gamma, the most two likely of which would give a beta and a gamma. So you'd be ingesting a dual beta gamma emitter.

Now, to find out how far would those betas go, as in are they energetic enough to escape you or not, what do you use?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: [INAUDIBLE] electrons.

AUDIENCE: Calculations.

MICHAEL SHORT: Back to calculations. Or I want to show you guys there is a database for everything and it's always on NIST. I wonder if any of you guys have found these for the homework because I didn't use them in the solutions, but they're quite useful.

NIST has a database called ESTAR, stopping powers for electrons where you can simply say graph the total stopping power or range for electrons in elements or materials. Materials, let's call food as soft tissue. They don't have that, let's go to water. And it gives you the range of electrons in grams per square centimeter in water. What do we have to do to make this into an actual range in centimeters?

AUDIENCE: You divide by density.

MICHAEL SHORT: Multiply by density. Yeah, I'm sorry, divide in this case. So you have the range in grams per square centimeter. If you divide by density you're left with centimeters on the top. The density of liquid water is about 1. So in the case of water, you can simply read off this table if you're talking water at 25 C. So a beta particle with an energy of about 1.5 MeV has a range of about a centimeter in material. Not something you'd want to ingest because around 1 centimeter away from wherever the betas end up they would do a whole lot of damage at the end of their range where they have the highest stopping power.

So we for many, many reasons, least of which is activation, neutrons are out. So we do not irradiate food with neutrons because they will induce radiotoxicity. So for anyone that tells you, oh, don't you stick food in a reactor to irradiate it, the answer is definitely not. You don't want neutrons nearby. So we're left with different types of betas and gammas.

From our study right here we just found out that betas penetrate about 1 centimeter into materials at 1.5 MeV. So how energetic do we have to get them to get to the center of the chicken? If range is proportional to t squared and our range at 1 MeV or 1.5 MeV is about 1 centimeter-- if we want to go to 20 centimeters, about how much more energetic do we have to get the betas to irradiate the whole chicken?

AUDIENCE: At least 10 times [INAUDIBLE]. Probably.

MICHAEL SHORT: Let's go with 10 times. Let's go to 15 MeV, and we can just read off this chart. At 15 MeV we're getting on about-- now keep in mind, this appears to be a double log scale, so that right there is 10, that right there is 100. Yeah, we're getting towards 10 centimeters. If we want to see where it is at 20, the log marker line is kind of missing, but it comes to about here. If we go down, we're getting around 30 or 40 MeV.

How reasonable does that sound for linear accelerator? Fairly. It's not unreasonable. It would still be big. Yeah, it may not be efficient, so we may not use betas to irradiate entire chickens.

What if you're irradiating strawberries that are roughly about a centimeter in diameter? How does a 1 MeV linac sound? We've got some of those. Yeah. We've got a 2.5 MeV linac just down the street in building N40. So that's totally OK. You could use betas in order to irradiate thin enough foods, food for which you can reach the center with the range of the betas. Do you induce any significant radiotoxicity? How do you find out?

AUDIENCE: Experiments.

MICHAEL SHORT: You could run an experiment. Or what database would you jump to to try to figure this out?

AUDIENCE: Janis.

MICHAEL SHORT: I would jump to Janis. So let's go back there. Let's see if they have the incident electron data. Yes, incident electron data, the EXFOR database. It's good for charged particles. Let's look at iron 56. Let's say you're irradiating red meat. I think this is just total cross-section, so that's not going to tell us much. It's also not loading and had an error, and another error. Interesting.

All right. Let's see if we have any other interesting isotopes that have any good reactions. Guess not. All right. Well at any rate, it's awfully difficult to induce radiotoxicity with betas. There's another one I didn't get into, which would be protons, somewhere between alphas and betas in terms of range and such. Does anyone know, perhaps anyone that works in the vault, what happens when you give very high energy protons?

AUDIENCE: A lot of gammas and neutrons.

MICHAEL SHORT: Indeed. A lot of gammas and neutrons. The gammas, maybe no problem at the irradiation facility; the neutrons, big problem. So find it again. We head to Janis, look at the incident proton data. I've already scoped this out and I know it's on the EXFOR database of cross-sections. Let's go right back up to our iron 56. So assume we're irradiating red meat.

What sort of reactions do we have? Proton, n, something with a few points to it. A-ha, a non-zero cross-section. So typically in the range of five to 10 MeV, high energy protons will start to create neutrons where a proton will come in, a neutron will come out. So you would absolutely not want to use protons above, let's say a safe limit, of around 3 MeV. Then the problem is what's the range of 3 MeV protons and stuff? Anyone have a intuition for that? Pretty small.

If you don't know generally the order of magnitude, we'll head back to here to TRIM. We'll use 3 MeV protons. It's looking about a millimeter of material. We're getting about 200 microns in.

Not useful enough to be useful for any sort of food irradiation. So protons again are out for reasons of both neutron activation and range.

AUDIENCE: When people [INAUDIBLE], it's like I sit next to it all the time.

MICHAEL SHORT: Sure. But what energy are the protons that you're making?

AUDIENCE: Well, I mean we did a lot of low energy, but went down to like 10 MeV.

MICHAEL SHORT: I highly doubt you were sitting there during 10 MeV.

AUDIENCE: I think the highest we've gotten was probably 2 or 3.

MICHAEL SHORT: Yeah. So 2 to 3 MeV, those proton cross-sections jumped to 0. In fact, let me show you that for a better-- kill the TRIM thing because that'll fry the computer. Let's look at, I don't know, carbon, where there's a whole lot more data, natural carbon. There should be lots of nice cross-sections here. So in goes proton-- maybe not for natural. Carbon 12 has over 100 different reactions. Something, n.

Well, there's a lot of reactions to sort through. Well, I don't want to waste your time with that now. But anyway, hopefully the cross-sections I showed you show you that around 5 MeV or so you do start to make neutrons. So if you can get up to 10 MeV, that's why the vaults got that forefoot thick door. You don't want to be in the room when that happens.

AUDIENCE: When we do a lot of protons in class is not shielded.

MICHAEL SHORT: Yes. But the class accelerator only goes up to about 2 MeV. Yeah. And that's perfectly safe to be standing around there for.

AUDIENCE: We have downstairs we can't next week because interlock.

MICHAEL SHORT: Yep. Because of interlock, but not because of physics, right?

AUDIENCE: I'm in both.

MICHAEL SHORT: OK, fair enough. Cool. So now we're left with gammas. Gammas work pretty well. They have very, very long ranges. Even the concept of range of a gamma is kind of a funny thing to say because they undergo exponential attenuation. So you want either a high enough flux of gammas that their low attenuation won't matter or you use a lower energy gamma ray.

So cobalt 60 irradiators that give off those 1 and 1/2 MeV gammas are quite commonly used for this sort of thing because the 1 and 1/2 MeV gammas will get through just about everything. You just need a whole lot of them. Has anyone here seen or heard of the cobalt irradiator downstairs in the basement building six? We got one of these things actually. It's just a sealed source of cobalt. And the way you start irradiation is you simply open the door and the irradiation stops being shielded enough. Now, what things could go wrong with super high energy gammas?

AUDIENCE: Ironizations.

MICHAEL SHORT: Ironizations is what you want, right? You want to ionize the water and the DNA of the bacteria or the germinating cells so that they get destroyed. What else could you induce with super high energy gammas?

AUDIENCE: [INAUDIBLE] electrons.

MICHAEL SHORT: That's another form of ionization, right? So that's a good one. Why don't I show you a quick thing? Let's go to incident gamma data. I think the EXFOR database will be pretty good. Let's go back up to iron again. We'll go with our red meat example. Gamma, neutron.

Anyone heard of gamma induced neutron ejection? High enough energy gamma rays will actually cause neutrons to be emitted. So gammas are a definite yes from the point of view of physics. They're also going to have to be less than about 5 MeV because once you get to around 5 MeV, or in the case of iron 56 10 MeV, you end up with a non-zero. And actually fairly significant like 0.1 barn cross-section for a gamma goes in, a neutron comes out, and that neutron comes out at whatever energy. It activates what's nearby and makes all sorts of nasty isotopes that decay the way they will.

Do you guys remember too from the neutrons discussion about photofission, the idea that a gamma ray can induce fission of a heavy nucleus? So if there's any traces of uranium in the food, which there always are, whatever, what you don't want it to do is then make a whole bunch of fission products because even a couple parts per million of uranium which might be no big deal could be a big deal if you turn it into fission products instead of plain old uranium where it's just a heavy metal, like lead, whatever. We can deal with a tiny bit of lead in our food. Totally.

Yeah, OK. So while looking through these internet studies talking about-- I don't like this kind of argument number four, irradiation encourages filthy conditions. I don't think that's a fault of the irradiation. I think that's a fault of the people who are like, oh cool, physics means that we can relax our standards. These are separate arguments. And going through all these things that, frankly either are false, are true, but the question is how much, and are true to such a small degree that it barely matters. And wading through a lot of these things, let's say, PhD thesis, articles in the ecologist, a lot of other FDA papers, various filings, from the '60s came upon actually a really useful document, this World Health Organization study on the wholesomeness of food irradiated with doses above 10 kilogray. It's modern. It was done by a peer reviewed study group. It was commissioned for a major organization, so I pulled it up. Yeah. It's like, OK, there's a legit reference in here.

I recommend you guys look through this. It's quite fascinating how many studies have been done on rather higher irradiation doses. So you can usually get away with stopping germination at around a kilogray or so, rather low dose of radiation. The highest dose anyone would use is about 50 kilogray. They specifically looked at the highest order of magnitude dose that we use for food irradiation and looked not just to say are there ill effects, but what are the ill effects? What are the other compounds that are made, and do they matter in the end? And I want to walk you guys through a few of the bookmarks that I found pretty fascinating.

I asked you guys about G-values at low and high temperature. Here's a great plot showing that right there. This is food irradiation done at 20 and minus 40 Celsius to look at the amount of ammonia, nitrates, ferrocyanides, things that you might not want, and look at the difference between irradiating at 20 C and minus 40 C. Enormous. Why is that so, physically?

AUDIENCE: Diffusion stops.

MICHAEL SHORT: Exactly. Diffusion stops when you cease to have a liquid. It doesn't stop completely, but the diffusion constant of anything and a solid it's going to be a whole lot slower than that same anything in a liquid. And so this way you can destroy the cells without all of the radiolytic byproducts going around and damaging other food molecules and other food cells.

Then we got into the question of off smells and funny sorts of changes. So one of the comments said can change the flavor odor and texture of food, pork can turn red, beef can smell like a wet dog, vegetables could become mushy, et cetera, et cetera, et cetera. This review of studies actually looked at what compounds are formed in which foods, and by how much? The only thing they didn't tell you is how do they smell? So I looked up a few of those. They looked at hexanes as a function of fat content for a rather high dose for 10 kilogray, or at least here everything is in normalized per 10 kilogray.

So this is the yield of this compound in nanograms per gram. Does that sound like a big deal? It may not sound like a big deal, but a lot of these odiferous compounds are detectable by the human nose in parts per billion. So they actually do matter. And I looked up to see what sort of smell do hexanes typically have? The word was petrolic, smelling like petrol or gasoline. Might not necessarily be something you want.

And it is true that fat compounds when you break up these, let's say, fat molecules, which usually contain three fatty acids, those fatty acids themselves are very aromatic. You've heard that expression fats where the flavor is, right? A lot of it is not just due to, well, if you just eat butter, it's not that flavorful. Anyone ever tried? I'm glad I'm not the only one. OK, good.

But where fat really comes into play is when you heat it and it undergoes all sorts of different chemical reactions with the food nearby, liberating some of the fatty acids. It's part of why lamb smells like lamb and nothing else, is fat's where the flavor is, and 90% of flavor is smell. You've only got five or six tastes I think that's still under the debate, but you can smell thousands of different compounds. And so they actually matter.

So I started looking at some of the other ones. Heptadecadiene in micrograms per gram fat per 10 gray for foods containing a lot of linoleic acid. The smell, Carrion beetle sex pheromones. The sex pheromones shouldn't be what turns you off, it should be the Carrion beetle. What is Carrion? It's the beetles that feed on rotting meat. So this is the juice that rotting meat beetles secrete to attract other rotting meat beetles nearby, to use polite language. It's probably something that you don't want in your food, or is it? Does anybody know what makes pork smell like pork? Is what?

AUDIENCE: Do I want to know?

MICHAEL SHORT: You're going to find out. Who likes pork here? Awesome. I'm going to ruin your day. There's a compound called skatole. Can anyone figure out from the root of the word? Yeah. Anyone ever heard of that wonderful barnyardy smell from a cut of free range pork? Anyone heard this term before? Just raise your hands. Anyone heard the nice pork barnyardy smell? OK, a couple of people. That barnyardy smell is parts per trillion or parts per billion of skatole. So tiniest littlest bit of poop. Yeah. The same sort of compounds that you find in scat in incredibly small amounts contribute to the wonderful flavor of really good pork.

So just because these compounds are made in higher amounts with higher amounts of fat or dose doesn't mean that they're necessarily off flavors. But it is kind of hilarious to see what other places do you tend to find high concentrations of these?

The next one down, hexadecatriene from irradiation of muscle. The one paper I could find that talked about this in a cocktail of smell compounds comes from the odiferous defensive stink glands of red something beetles. Yeah, sounds horrible, right? So if you stopped there you might think, great, so radiation produces odiferous defensive stink gland compounds. But as we know, pork smells great. We don't necessarily know in what concentrations-- what is it? -- hexadecatriene would smell good or smell bad to the human nose. It's just no telling.

There's some compounds in any amount if you can detect them they're terrible. There's some compounds that go from bad to good. There's some pounds that go from good to bad. Anyone ever smell someone that's slopped on perfume before? Would you describe the smell as good? No. Perfume relies on lots of different compounds in very, very small concentrations. It's supposed to be subtle and enhance your own body chemistry. You're not supposed to smell like a perfume factory explosion. So another sort of real life analogy where too much of a good smelling thing can smell really bad. Yeah.

And so then going on from the various odiferous compounds where a few other points I wanted to-- oh no, there's another one. OK. Seems like the production is pretty much linear with either dose or with the abundance of the precursor normalized dose. This one you tend to find in deodorants. What was the name of this compound? Propanediol type. Don't know the structure because I'm not an organic chemist, but things you might find in deodorant. Again, no telling whether or not this would be good or bad in food and how much. That's always the question I want you to remember. If somebody asks, isn't binary effect bad? Isn't meta tag binary effect bad? The question is depends how much. Yeah?

AUDIENCE: Do these like graphs show how much more more there was afterwards or just like how much there is in general?

MICHAEL SHORT: They do. It shows the dose normalized yield per 10 kilogray in micrograms per gram. So it shows that depending on how much of whatever precursor, in this case enzyme inactivated muscle there was, how much relative amount of this compound existed. What these graphs are telling us is they're pretty much all linear and they're pretty much all the same for-- I saw that as human for a second, holy crap. My heart just skipped a beat. --ham beef, chicken, pork. Oh man.

Anyway, going into the conclusions, which again are strikingly different than the internet article would have you believe, I wanted to point things out. Interesting. Irradiating moist foods while frozen in the absence of oxygen significantly decreases overall chemical yields by about 80% So it's interesting you can irradiate something to 50 kilogray at minus 30 C and it does the same chemical change as 10 kilogray at room or chilled temperatures, but you do that much more damage to the organisms. So yeah, there you go, better to irradiate at cold temperatures.

And there's a few other interesting conclusions. These radiolytic compounds, are they found in food otherwise? Virtually all the radiolytic products found in high dose irradiated foods are either naturally present foods or produced in thermally processed foods. Before food irradiation you had heat sterilization. In fact we still do for quite a bit. And folks, a lot of times we'll talk about the amount of nutritional decline, the amount of lack of nutrition from irradiated foods, and they'll just say it's a bad thing. That's not the right fact to see here. Food preservation tends to lower the nutritional content.

And there's a few neat tables I want you guys to look at. In terms of macronutrients, do you lose the protein, the fat, the carbohydrates from in this case, gamma-irradiated mackerel, as a function of dose? Does anybody see a trend here? Take a sec to look at the numbers.

AUDIENCE: Seems like it bumps in the middle.

MICHAEL SHORT: It does seem like the nutritional content goes a little bit up with small doses, doesn't it? Would you necessarily believe these data at first glance or at face value? What's missing from this data set for you to draw a statistically significant conclusion?

AUDIENCE: Error bars.

MICHAEL SHORT: Error bars, right. If this is the graph of, let's say, protein content versus dose in gray and this is protein, the data appear to do something like this. If the error bars are like that then you can't draw any meaningful conclusions. So one would have to go back to the study to see hopefully they actually had error bars in their measurements. So what I can conclude from this is macronutrients basically don't change with up to the highest dose of radiation that we give to any food at all.

What about the micronutrients? What about things like vitamins? They do go down somewhat, and they're pretty linear. They're fairly linear with dose. It's not much to be disputed there, is yes, irradiating food does destroy some of the vitamins and not the minerals. Why wouldn't gamma irradiation destroy minerals in food? What's an example of a mineral that you need for survival?

AUDIENCE: Iron.

MICHAEL SHORT: Iron.

AUDIENCE: Calcium.

MICHAEL SHORT: Calcium. Yeah, bunch of other elements or inorganic compounds. Why does food irradiation not affect mineral content?

AUDIENCE: If you use low enough energy gammas it's just not going to change paratonic.

MICHAEL SHORT: That's right. Yeah. You stay below 5 MeV gammas and there's literally no change in the elemental composition of those minerals. The vitamins, however, tend to be more complex organic compounds that can be damaged. And one of those big ones is thiamine, better known as vitamin B1. So irradiated food is a little bit less nutritious, but they give a pretty good explanation. Let's see. Think that's later in the conclusion, so we'll get to that. Conclusions on nutrition. Yeah, there we go.

So in this case, what they're saying is, well yeah, it takes away some thiamine, but irradiated food does not constitute the major source of thiamine in the diet. So even though it does reduce the amount of thiamine that you get, it doesn't make a dent in your overall nutritional uptake unless you eat nothing but that irradiated food.

Does anyone remember when the last case of scurvy in the US happened? Talking about single food diets. Happened right here at MIT. It was a while ago. I think by now it would have been over 10 or 15 years ago.

There was a student that decided I'm going to have the cheapest food budget ever and live off nothing but instant packs of ramen. Now, this is already a nutritional nightmare, but it got worse and worse. So it was the ramen, the flavor packs and water, and that's just what this person ate the whole time. And then they decided, you know what? I don't really need the flavor pack because that's just a bunch of sodium, taking out whatever little micronutrients were left. And then the next logical step was why bother cooking it? And a few weeks later massive constipation and scurvy ensued, which is a disease you don't see anymore, from a deficiency of vitamin C. So if you're only eating one food to begin with you've got other problems have nothing to do with food irradiation. Yeah?

AUDIENCE: I'm not even surprised that the last case of scurvy was an MIT student.

MICHAEL SHORT: I'm not surprised at all either. I'm surprised Soylent wasn't invented here. It seems like the kind of thing that someone here would have done. Anyway, let's take a look. Ah, irradiation versus heat sterilization. From a nutritional viewpoint, irradiated foods are equivalent or superior to thermally sterilized foods. Why do you guys think that might be?

AUDIENCE: They're really sterilizing it with denaturing most of the proteins.

MICHAEL SHORT: Indeed. So you'd actually get some macronutrients to disappear if you start to denature or break down those, and even for micronutrients. The idea here is that the amount of micronutrient content will go down roughly linearly with dose. What happens when you reach the temperature of destabilization of those foods?

AUDIENCE: [INAUDIBLE] dropped them.

MICHAEL SHORT: Yeah, all of it goes away. Once it's temperature unstable, if you keep it at that temperature for long enough you'll destroy pretty much all the nutritional content. So if the choice is between do you heat or do you irradiate, irradiating does less damage in the end. Anyone here ever had an MRE, a Meal Ready to Eat? How do they taste?

AUDIENCE: They're not great, but they're not awful.

MICHAEL SHORT: But they do last for like decades, like many decades. There's an entire channel on YouTube of this guy that just eats MREs from further and further back. I think he's made it as far back as the Civil War and ate actual moldy hard tack from the Civil War. But my point here is that all the way back to definitely to World War II and perhaps beforehand, MREs were sterilized with heat.

You put something in a metal and plastic lined bag to keep out all other organisms. You heat it for long enough to kill every single other organism and they last for decades. And the question is, do you want to eat what's in the bag? If you want some fun between studying for finals listen to this guy's reaction as he eats some of these 60 or 70-year-old MREs from World War II of the Korean War.

AUDIENCE: Why would they subject themselves to this?

MICHAEL SHORT: I don't know, for attention.

AUDIENCE: [INAUDIBLE] gets stung by a really painful insect, and I will say why?

MICHAEL SHORT: Yeah. At any rate, canned food you can tell has an awfully different taste to it. A lot of these cans are heat sterilized. They're pasteurized and the heat themselves generates a lot of off flavors that you can tell the difference between fresh and canned green beans in taste, texture, color, mushiness, whatever other qualifiers you give to food. So to those opponents of food irradiation, I'd say consider the alternatives, either heat sterilization or spending most of your waking hours in the bathroom.

AUDIENCE: How do you like thermally sterilize meat without cooking it? I've always been really confused about that.

MICHAEL SHORT: Yeah, you can't necessarily. There are also spores of bacteria that are incredibly heat tolerant. So you can't necessarily sterilize meat without cooking it. So the best thing to do is to cook it, sealed in a can, or sealed in something and then don't unseal it until consumption time.

Yeah. There are other things that you can sterilize without cooking them, like milk. Milk is pasteurized. You heat it to a temperature that's sufficient to kill most of the microorganisms not to sterilize it, but to increase its shelf life so that it takes months instead of hours for that microorganism population to bloom and ruin the milk. I'm sure everyone here has smelled spoiled milk before, right? Doesn't matter how pasteurized it is. Has anyone opened a carton of expired milk after its shelf life?

AUDIENCE: One time I poured it into my cereal.

MICHAEL SHORT: Yeah. That was a study in two phase flow, right? Liquid, solid. Yeah. Yep. So there is some proof right there, a few bacteria survive. It's the same thing with food irradiation, you need an enormous dose in order to actually sterilize the food. So this is usually the only option for folks with extremely compromised immune systems in hospitals is if you want to give them actually sterile food that's actually palatable, you irradiate it to like 50 kilogray. And that kills just about every single organism including the long lived spores.

One other side benefit of food irradiation is the cells that survive have been blasted by radiation. They tend to be a lot weaker and more sensitive to heat and pH and temperature-- heat, temperature, the same thing. --so that the cells that make it through the food irradiation are more susceptible to damage and then it helps make things a little bit safer.

I'm trying to see if there's any other conclusions. Oh yeah, the old who cares about thiamine. It's unlikely however, that the irradiated foods of this type would constitute a large enough proportion of the diet to compromise the dietary requirement for thiamine. And this is coming from the World Health Organization. If there's any organization you think you can trust about health everywhere, it's the WHO, it's these guys.

And I don't think we have time for more of the conclusions, however I will post this document up to the learning module site so you guys can peruse at your leisure along with the bookmarks, unless I've done it already. Want to open it up the last two minutes to any questions you guys may have about anything, including final logistics, how it's going to all come down, the review session on Friday, whatever you guys want.

AUDIENCE: So the review is 9:00 to 10:00 on Friday?

MICHAEL SHORT: Yep. The review is 9:00 to 10:00 or 10:30, whenever we finish on Friday. I'll email out with a room once I secure one. Yeah?

AUDIENCE: Where do they usually do food irradiation?

MICHAEL SHORT: There are gamma irradiation facilities where they've got these cobalt 60 or cesium sources. No, this would be processing centers. Yeah, I mean you can't normally own one of these giant cobalt sources so. These would be specialized processing centers. Yeah?

AUDIENCE: So is this usually only done for foods coming in the US from outside?

MICHAEL SHORT: Oh no. It can be done for foods grown within and for the consumption in the US too. If you want to extend its shelf life by small or large amounts you can do it for anything, but there are a number of different types of produce that can only be imported because of food irradiation.

One of these that I was delighted about was mangosteens from Thailand. Mangosteens probably almost no one here has ever even heard of or seen. I'm surprised anyone has. OK, wow, two, that's a record. They're usually only found in South or Southeast Asia. They don't tend to last very long and they tend to be riddled with parasites. But one time out of two that

I've opened up a mangosteen, a whole bunch of bugs started crawling out. You'd imagine that the US doesn't want that imported into here.

But in 2005 Thailand started irradiating their mangosteens. They were approved for sale in this country and you can find them at H Mart now down the street. Even food from Hawaii has to be irradiated for consumption in the continental US. Why do you guys think that is?

AUDIENCE: Human species.

MICHAEL SHORT: According to the USDA, Hawaii is effectively a different country when it comes to the sorts of parasites you'd find in the food. It is a part of the US, but it is not agriculturally a part of the continental US. It's got its own unique parasites and pathogens and organisms and critters. So a lot of things coming from Hawaii have to be irradiated for consumption in the continental US. So yeah, food irradiation helps food commerce go around. Any other questions? Yeah? No, it's you.

AUDIENCE: What percentage of food actually gets irradiated?

MICHAEL SHORT: I don't know what percentage of food gets irradiated. It especially depend on the type. There's some things that don't need it. There's some things that do need it. I'd wager a guess to say that more imports get irradiated than domestic consumption stuff, but I don't know that for sure.