**Physics 408: Physics and Society Lecture 9: Nuclear Physics**

**[Instructor]**

**Slide #1**

**Physic 408 Physics and Society**

Physics 408: Physics and Society

Lecture 9: Nuclear Physics

**Audio:**
Physics and Society. Lecture 9. Nuclear physics.

**Slide #2**

**Topics for This Lecture**

Topics for This Lecture

- Properties of nuclei
- History of nuclear physics
- Nuclear model
- Nuclear mass
- $E=mc^2$
- Radioactivity
- Decay chains
- Curve of binding energy
- Fission and fusion
- Stellar evolution

**Audio**:
In this lecture we'll be discussing a variety of topics related to nuclear physics: the properties of nuclei, the history of nuclear physics, nuclear models, nuclear masses, $E=mc^2$, radioactivity, decay chains, the curve of the binding energy, fission, fusion, and stellar evolution.

**Slide #3**

**Properties of Nuclei**

- Nuclear—not nucular!
- Need for approximation—the one legged horse
- Chart of nuclides: http://www.nndc.bnl.gov/chart/
- # protons: Z
- #neutrons: N
- 109 known elements
- ~2000 different nuclides
- Atomic mass: A=N+Z

- Notation for element X: ${}^{a}_{z}X_{n}$
- Isotopes=same Z and varying N

**Audio:**
I wanted to start out this lecture by pointing out one of my pet peeves. The word is nuclear; it is not nucular as some past presidents have said. Nuclear. That's a word I'd like you to practice saying. Repeat after me. Nuclear. Good. Now that we have that straight, we've talked in the past about the need for approximation and that's very true in nuclear physics. The reason is that the nucleus is a very complex place. I told you that the theory of atoms is one of the most successful theories that exist. This is because the electrons that make up the orbits around the nucleus are very, very far away from the nucleus and they're generally, what we'd say, very far away from each other. Now in a quanta-mechanical sense, they overlap with each other, but we can treat them precisely and we can write down exact equations for the forces with which they interact which are basically the electromagnetic force. The nucleus is controlled by both the strong force and the weak force. We cannot write down analytical expressions for either the strong force or the weak force; instead we must make approximations. Now I thoughts I'd take a minute now and tell you a physics joke; the physics joke is about the one-legged horse. So it seems there was a very wealthy man who wanted to own the fastest possible horse so he hired a biologist, a chemist, and a physicist to come up with the fastest horse so he could be the winner at the races. So pretty soon the chemist came back and said he's got the fastest horse, he's come up with some really super drugs, this horse is fast, and sure enough it was a very, very fast horse. Well, about a year goes by and the biologist comes up and says he's got it licked, he's got the fastest horse because he's looked at all of the genetic strains that go into a horse and he's got this horse that has the best possible horse based on genetics and sure enough it was a very, very fast horse. So the wealthy man waits another year and doesn't hear from the physicist and so he goes to the physicist and says the chemist came back and the biologist came back with a very fast. What's going on with your horse? And the physicist said, "Well, I've solved the problem for the one-legged horse." Okay, so a physicist thinks that funny; it's funny because it's an approximation to a horse. The point being that nuclear physics works with a lot of approximations and we often work with one-legged horse models because we can't describe it exactly. So getting back to the subject of properties of nuclei, there is something called the Chart of the Nuclides. It lists in the same way that the chemical chart lists the properties of chemical elements, it lists all of the known nuclei, both stable and radioactive and there's a web link shown here of a very good place to get an interactive Chart of the Nuclides where you can look up properties of any nucleus. There are, as we indicated, something like 109 known elements, but there are well over 2000 known isotopes. There are many nuclei that have as many as a dozen isotopes that are stable or radioactive, but long enough lived that they remain together and can be called a nucleus. The nucleus is made up of protons and neutrons. We designate the number of protons by Z which is the atomic number and the number of neutrons by capital N. The atomic mass is the number of neutrons plus the number of protons, Z, and it's designated by a capital A. We have a notation we write down for an element so if we have an element we write it down as a symbol like O for Oxygen, for example, and the upper left corner represents the atomic mass, A, and the lower left corner is the number of protons, Z, and the lower right corner is the number of neutrons, N. Now, very often, since this is redundant information, we don't put this down. If you put down the element, X, and the atomic mass, A, you've really fully designated that nucleus because X represents the element. The element determines the Z and A

minus Z is N, but I just present this because it gives the complete notation that is used in physics. There are 109 known elements, as I said, and over 2000 different nuclides or isotopes. What is an isotope? An isotope is an element. It has a certain number of protons which is equal to the number of electrons, but the number of neutrons varies. So an isotope of oxygen, there are isotopes O sixteen, O seventeen, O eighteen, for example. They all have eight protons, but they have eight or nine or ten neutrons. Those are isotopes. We'll be using this terminology as we go along in the course.

**Slide #4**

**History of Nuclear Physics**

- 1895—Roentgen discovers x-rays
- 1896—Becquerel finds U salt fog films
- 1897—Thompson discovers the electron
- 1903—Curies gets radiation burns
- 1903—Rutherford & Soddy "radioactive change"
- 1905—Einstein publishes $E=mc^2$
- 1907—Rutherford notes "scattering of a rays"
- 1911—Rutherford measures a scattering
- 1911—Rutherford announces a nuclear atom
- 1914—HG Wells publishes "A World Set Free"

**Audio:**
Let's go through a brief history of nuclear physics. In 1895, Roentgen discovered x-rays. Now recall at the turn of the century, there were all these mysteries in physics that couldn't be explained. We talked about those in atomic physics. Here in nuclear physics we also have phenomena; there are these x-rays. Where'd they come from? What are they due to? Roentgen put a high voltage across a vacuum tube and observed the production of these rays that could penetrate through opaque materials. In 1896, Becquerel accidently found that uranium salts fogged film. He placed a rock on top of a piece of film enclosed in a package and then later developed it and discovered the piece of film had been ruined apparently by radiation being emitted by something being emitted from this rock that that had been set on top of this film. He made that leap of discovering the fact that the rock was the source of fogging the film. Again, what was this due to? In 1897, JJ Thompson discovered the electron. You have to remember that up to this point, atoms were a concept, but the components of atoms weren't known. Here was the discovery of the first components of the atom, the electrons. In 1903, the Curies, Madame Marie Curie and her husband, Pierre Curie, were playing with radioactive materials, salts derived largely from pitchblend, and they managed to get radiation burns, one of the first instances of that. In the same year 1903, Rutherford and another researcher, Soddy, in England, noted that there was this idea of a radioactive change, something's happening in certain materials that were changing their properties. In 1905, Einstein published his very important equation, $E=mc^2$. Recall that Einstein, in 1905, published three papers. The first was the explanation of the photo electric effect that we talked about when we talked about atomic physics, for which he got the Nobel prize. The second paper was on Brownian motion, the random motion of small objects observed through a microscope due to the jostling of molecules pushing it around. The third paper was on special relativity and that's where he wrote down this equation that energy

equals mass times the speed of light squared. This was to be of tremendous consequence over the next many decades. In 1907, Rutherford, who was a young faculty member, made a note that one of the things he wanted to investigate was the scattering of alpha particles or alpha rays and, in fact, four years later he carried out those experiments and he came up with a very surprising result. He has shown alpha rays which are given off by some materials, such as those that the Curies had investigated, onto thin, gold foils and then he had people sitting in dark rooms observing what happened to these alpha particles after going through this gold foil and what he found was two very important facts. The first was that most of the alpha particles went right through the gold foil without being deflected or anything happening to them; that was strange. That implied that this material was basically empty. Most of the material was just empty and alpha particles would just go straight through it, but the second thing he noted was that some alpha particles were scattered to very large angles. He likened this to a piece of tissue paper might divert an artillery shell off to a large angle. It was that clue that allowed Rutherford to derive in 1911 and announce the concept of the nuclear atom. The fact that an atom consists of a very, very small tiny large mass nucleus and a completely empty atom with electrons on the outside. So this concept of a nuclear atom was brand new and it matched well with what Bohr had talked about in terms of an atomic model. In 1914, HG Wells, the well-known author, wrote a very, very interesting book which I encourage you to read. It's called "A World Set Free". Here was HG Wells just before World War I and shortly after Rutherford discovers a nuclear atom speculating that there was a way to release the energy contained inside of a nucleus and this energy once released would set the world free, but he describes in this book a war that takes place in Europe and in this war bi-planes are flying and they're dropping these large bombs over the edge, these atomic bombs that do tremendous damage and destroy Europe. This book, apparently, influenced Leo Szilard, a Hungarian physicist, who around 1930 was crossing a London street and was struck by the concept of the chain reaction and realized he knew how to release the energy in the nucleus atom. More about that later.

**Slide #5**

**Nuclear Model**

- Plum pudding atomic model
- Rutherford atomic model
- Bohr later elaborated
- If a nucleus is 1mm, then the atom is ~100 m

[Image] *Examples of plum pudding model, Bohr atom shell model, Bohr nuclear shell model, and liquid drop model shown.*

**Audio:**
Let's talk a little bit more now about nuclear models. I told you that the nucleus if a very complicated place. Prior to Rutherford's work, the best outstanding model that existed was something called the plum pudding model. In this concept, the atom was this place where there were electrons smeared out over some volume and scattered throughout this whole volume were heavier pieces of matter somehow scattered. Remember, nobody knew about protons and neutrons at this point; they just knew that somehow the atom had mass; the electrons were very light because they'd been discovered by Thompson, and so this plum pudding model distributed

the mass throughout this space. It was this sort of model that Rutherford was testing when he put an alpha particle material he expected that the alpha particle would hit these masses scattered throughout the atomic space and that they would be scattered very easily most of the time. Well, that's not what happened so you then had this model that Rutherford came up with whereby the nucleus was this tiny particle in the middle and that somehow electrons were around the outside and that was matched up with Bohr's atomic model so we have this shell model of electrons on the outside, a very small nucleus, the electrons can be excited into the shells. What evolved then was the issue of what is the right model for the nucleus itself? We have this atom model which is small nucleus, large electron shells. What can we say about the nucleus? Well, over the next 20 years or so, a lot was discovered about radiation coming from nuclei and very much like atomic spectra, one gets nuclear spectra, one gets lines of "light" being observed coming out of a nucleus of an atom. That is, you get very specific energies of gamma rays coming out of the nucleus. Photons emitted by the nucleus are called gamma rays. Photons emitted by the atom, by the electrons are called x-rays. So these gamma rays had very specific energies. This led Bohr, the same Bohr, Neils Bohr, to come up with a model for the nucleus which was a shell model, the same sort of shell model he had come up with for the electrons. In this shell model, neutrons and, independently, protons formed shells and they could be excited and de-excited and there was a limit on how many neutrons and protons could go into any individual shell just like there were, in the atom, limits on the number of electrons that could go into any shell. So the concept was that nuclei get excited also and these individual neutrons or protons get excited to higher shells and they fall down to lower shells and in the process they emit gamma rays and, in fact, this model worked quite well and still works quite well, but it turns out the shell model is a good approximation for some nuclei; it's a bad approximation for some other nuclei and it's nowhere near as good of model as the atomic model for electrons. That's because of the nuclear force, the strong force and the weak force, is very complex and the neutrons and protons inside a nucleus are all very, very crowded together; they are all very close to each other. So Bohr's shell model is still used today; it predicts some properties of some nuclei, but not all the nuclei. In particular, big, heavy nuclei like uranium, for example, don't really behave very well like shells. Instead, they exhibit behavior like a drop of water. Imagine a drop of water suspended in the air. That drop of water can slosh around, it can vibrate, it can rotate, it can become dumbbell shaped, and move back and forth, and tumble. Those motions are described in what's called the liquid drop model and nuclei very often behave like liquid drops, particularly heavy nuclei. So what we have here is two approximations to how the nucleus behaves. On one hand, it behaves like a shell model. On the other hand, it sometimes acts like a liquid drop and real nuclei fall somewhere in between with very complex behaviors. So, there are many complex models of nucleus and, of course, all the time theorists try to improve those models and make them better and better. To put the scale of a nucleus into perspective, if the nucleus is one millimeter in size, then the atom is 100 meters in size. So I gave you the analogy of the football stadium previously. A pea at the center of a football stadium is about the size of a nucleus and that nucleus contains a lot of complex things. Physics tries to come up with models to try to describe it with some success.

**Slide #6**

**Nuclear Mass**

- 1 U=1/12 $^{12}C$

- 1 u=$1.66 \times 10^{-27}$kg
- $m_{proton}$=1.0073u
- $m_{neutron}$=1.0087u
- $m_{electron}$=.0005u
- Mass ($^{12}$C)=12u by definition
- But $^{12}$C=6 protons + 6 neutrons
    - =6(1.0073u)+6(1.0087u)=12.096u
- Why the difference of .096u?

**Audio**:
Let's talk about nuclear mass. The atomic mass unit, represented by the lowercase u, is defined as 1/12 of the mass of a carbon twelve atom. Carbon 12 is made up of 6 protons and 6 neutrons and 1/12 of that, by definition, is the atomic mass. If you translate that into kilograms, it's a small number, 1.66 times 10 to the minus 27 kilograms, is the equivalent of the atomic mass unit. In those units, a proton is 1.0073 atomic mass units. The mass of a neutron is 1.0087 atomic mass units. The mass of an electron is about 2000 times smaller than both of those or .0005 atomic mass units. You notice that the mass of the proton and neutron are slightly different. All of these masses require some explanation. As I said, the mass of carbon 12 is 12 atomic mass units by definition, but carbon 12 is made up of 6 protons and 6 neutrons so if I take the mass of 6 protons and add that to the mass of 6 neutrons, I get 12.096 atomic mass units. So for some reason, there's a difference between the mass of carbon 12 which is 12 atomic mass units and the mass of 6 protons plus 6 neutrons, 12.096 atomic mass units. 12.096 atomic mass units may not sound like very much, but in terms of energy, using $E=mc^2$ that we learned from Einstein, it turns out to be quite a bit of energy. The answer to the question what's the difference is what is referred to as binding energy. Binding energy also exists for electrons, but it's on a much smaller scale, about a million times smaller scale. The binding energy means that the mass has been converted into potential energy. The equation equals $mc^2$ says that mass and energy are equivalent and what happens is when these 6 protons and 6 neutrons get together and cram into a very small space the forces that hold them together to cause some of that mass to become potential energy. It's that potential energy difference that if released somehow, could be the source of energy for an atomic bomb or a source of energy for producing good.

**Slide #7**

**$E=mc^2$**

- The mass difference between 6 protons plus 6 neutrons and $^{12}$C is the binding energy
- Mass difference of .096u=$1.66 \times 10^{-28}$kg
- $E=mc^2=1.4 \times 10^{-11}$J (not much)
- But 1 mole of $^{12}$C is 12g with $6.023 \times 10^{23}$ atoms
- That mole thus represents $8.6 \times 10^{12}$J!
- Small amounts of mass hold a huge amount of nuclear potential energy, and it can be released
- Atom ~1 eV while the nucleus is ~1 MeV
- When a firecracker explodes ~$10^{-10}$ g converts to energy

**Audio:**
So let's put some numbers to this binding energy. The mass difference between 6 protons and 6 neutrons and that of carbon 12 is binding energy. The mass difference of .096 atomic mass units is 1.66 times 10 to the minus 28 kilograms. Converting that with $E=mc^2$ is 1.4 times 10 to the minus 11 joules. That's a small number but consider the fact that a mole of carbon 12, which is 12 grams of carbon 12 (12 grams of carbon 12 easily fits in your hand), has six times ten to the $23^{rd}$ atoms so that one mole of carbon represents 8.6 times ten to the $12^{th}$ joules of energy. Somehow you could release that binding energy that's in carbon. Now 8.6 times ten to the $12^{th}$ is a really big number. Recall that when we talk about nuclear power plants or regular power plants, we talk about one gigawatt electric power output. A gigawatt for one second is 10 to the $9^{th}$ joules. Here we have three orders of magnitude bigger of terms of energy release. This is a lot of energy. That's why an atomic bomb it doesn't take much mass to release a huge amount of destructive force. Now I said that the atomic scale and the nuclear scale of binding energy is different by about six orders of magnitude. To quantify that, as we've said earlier, the energies of atoms, atomic binding and chemistry, are all on the approximately 1 eV scale while the nucleus, the energies, are a million times bigger. They are on the approximately 1 MeV scale, millions of electron volts, a million times bigger. So when you go from the atom to the nucleus, you gain a million times in the energy of interactions of energies that are associated with that phenomenon. The idea that energy and mass are interchangeable can be appreciated a little bit when I tell you that when a firecracker explodes, there's a chemical reaction going on and the binding energy that's released in that firecracker explosion is with a chemical processes means that something like ten to the minus 10 grams of that firecracker are converted into energy. So a very little bit of mass is converted into energy and produces that bang that you see as a firecracker. Now imagine that being multiplied by millions of times and that's the destructive power that a nucleus contains.

**Slide #8**

**Radioactivity-Gamma Decay**

- Gamma decay—energetic photons emitted by the nucleus
- Nuclear shell model analogous to atomic shell model
- Neutrons and protons in nucleus are far more complex in structure than electrons in atoms

[Image] *Diagram of neutrons/protons and excitation increase PE ($E_i$ to $E_f$) and de-excitation releases a photon $hf=E_f-E_i$*

**Audio:**
One of the ways in which nuclei exhibit the energy content they have is through radioactive decay. There are basically three forms of radioactive decay: gamma decay, beta decay, and alpha decay. There are some others that we won't be touching on. Gamma decay can be thought of as exactly analogous to the emissions of photons by an atom that Bohr explained, such as the Balmer series. In the atom recall that the electrons would be excited to an outer shell, drop to a lower shell, and in the process emit photons of light. Those photons are in the visible or maybe even the x-ray regime. An analogous thing takes place in the nucleus. We talked briefly about Bohr's shell model for the nucleus. In this model, protons or neutrons can be excited to higher

shells thereby gaining potential energy and they can fall back down to lower shells and release that energy as photons in the same way that it happens in the atoms. And the energy difference between the excited shell and the shell it falls back to is equal to a constant, h, times the frequency of the light emitted. So gamma rays are photons emitted by the nucleus of an atom. The shell model is a simple analogous way to explain this and the neutrons and protons act independently in this. That is, you can get gamma rays emitted by neutron excitations or gamma rays emitted by proton excitations so that's another complication to this picture we have. In addition, there are other ways gamma rays are emitted are that are not associated with the simple shell model, but are associated with things like rotations and vibrations of the nucleus that were explained in the model dealing with what's called liquid drop. So, complex situation but at this point simplest to think about it as just the emission of photons by a nucleus.

**Slide #9**

**Radioactivity-Beta Decay**

- 6 decay—energetic electrons or positrons emitted by neutrons or protons in the nucleus
- Z changes by one unit and A stays the same
- $n \rightarrow p + e^- + \nu$
- $p \rightarrow n + e^+ + \nu$
- For example, $^{40}K \rightarrow {}^{40}Ca + e^- + \nu$

[Image] *Diagram of beta decay process*

**Audio:**
The second form of radioactive decay is beta decay. In beta decay, a nucleus emits an electron or it can emit a positron. Now a positron is a positively charged electron; it is the anti-particle of an electron. That is, if an electron and positron come together they annihilate each other and the only thing left behind is energy. So beta decay is emission by a nucleus of an electron or a positron. When nucleus emits a beta particle, it changes its charge by one unit. So the simplest forms of beta decay are a neutron decays to a protron plus an electron plus an object called a neutrino. The neutrino is a mass-less, charge-less particle that was speculated to resolve the kinematics, the motion of the particles in beta decay. The other form of beta decay is a proton can decay to a neutron plus a positron, positively charged electron, plus a neutrino. These two processes of conversion are both forms of beta decay. A very good example of beta decay is potassium 40. Potassium 40 is a naturally occurring isotope of potassium; it is radioactive. That is, it decays, but it decays over a very long period of time and when it does decay, it decays to calcium 40 plus an electron plus a neutrino. At the bottom here, I've drawn two pictures just to sort of schematically show what happens. The neutron emits these electrons and neutrinos and becomes a proton or a proton emits the positron and neutrino and becomes a neutron. This is beta decay.

**Slide #10**

**Radioactivity-Alpha Decay**

- α decay—energetic particle emitted by the nucleus
- Alpha particle is a helium nucleus (2 protons + 2 neutrons)

- Alpha decay causes the atomic mass (A) to drop by 4 u, Z to drop by 2, and N to drop by 2
- Long lived decay chains
- For example, $^{248}U \rightarrow ^{234}Th+a$

**Audio:**
The third type of radioactive decay is alpha decay. It is the emission by a nucleus of a heavy particle. The particle emitted by the nucleus is two protons plus two neutrons. That is, the nucleus of a helium atom. So imagine a heavy nucleus spitting out this alpha particle, these two protons and two neutrons coming out of it. That's alpha decay. Alpha decay causes the atomic mass, A, to drop by four units, the charge to drop by two units, and the number of neutrons to drop by two units. For example, uranium 238, one of the uranium isotopes, decays by emitting an alpha particle plus a thorium 234 nucleus. That is, the uranium becomes thorium plus an alpha particle. These types of decays continue. Thorium 234 isn't itself radioactive and, again, decays as we'll see shortly. In general, these alpha decays occur through a series of long-lived processes. Uranium 238 has a lifetime of billions of years, but eventually it ends up decaying through a decay chain as we'll see.

**Slide #11**

**Half-life**

- When radioactive nuclei decay, it is an exponential process characterized by its half-life—the time for half the nuclei to decay
    - Start with 100 nuclei
    - After one half-life, have 50 nuclei
    - After two half-lives, have 25 nuclei
- Some half-life examples:
    - $^{238}U$: $t_{1/2}=4.5x10^9y$
    - $^{40}K$: $t_{1/2}=1.3x10^9y$
    - Neutron: $t_{1/2}=10.6$ minutes

**Audio:**
When a radioactive nucleus decays, it's an exponential process characterized by a quantity called its half-life. The half-life a radioactive material is the time it takes for one-half of the nuclei to decay. So for example, if you start off with 100 nuclei, after one half-life you have 50 left, after two half-lives you have 25 left, after three half-lives you have 12 le ft, and so forth. Half of them are gone in each half-life. Some examples of this are uranium 238 which is the predominant form of uranium that's found has a half-life of 4 ti mes ten to the 9th billion years. That's quite a long time. The earth is only about 5 billion years old so a half-life of 4 bil lion years means that during the entire time the earth's existed about half the uranium in the earth has decayed away. As we'll note later, this radioactive decay of uranium and other materials like thorium and potassium are actually what provides the heat that keeps the earth hot on the inside. Another example is potassium 40. Potassium 40 is one of the isotopes of potassium found in nature. It also has a very long half-life, 1.3 times 10 to the 9th years, 1.3 billion years. Not quite as long as uranium so since the earth was formed or actually since the elements were produced in the start that exploded that produced the potassium the amount of potassium has decayed away.

So in the 5 billion years or so the earth has been around, it's been roughly three half-lives, three or four half-lives. So if it's four half-lives, that means that 2 times 2 times 2 times 2 or the factor 16 has occurred in the amount of potassium; the amount of potassium today is 1/16 of what was here in the earth 5 billion years ago. So in the other extreme, another example of a half-life is the neutron. A free neutron outside the nucleus decays and it decays with a half-life of 10.6 minutes so if you have a bunch of free neutrons, half of them will be gone in 10.6 minutes. You'll only be left with ¼ of them after 21.2 minutes and so forth. That's the consequence of half-life. Half-lives of radioactive nuclei exist on all scales. There are some nuclei that decay very, very quickly, a femtosecond, ten to the minus 15 seconds and there are nuclei that live for billions of years and there are nuclei that are everywhere in between so there's a whole range of half-lives depending upon the process by which decay occurs and the specific isotope.

**Slide #12**

**Decay Chain Example**

[Image] *Diagram of an example of a decay chain of certain elements*

**Audio:**

I mentioned that some of these heavy nuclei go through what are called decay chains. This is a string of radioactive decays that occur that ultimately lead to some stable element isotope. So take the example of uranium 238 that we talked about, half-life of 4 bil lion years. When uranium 238 decays, it decays to thorium 234. Thorium 234 has a half-life of 24 days so in 24 days half of it's gone and it decays to palladium 234. Palladium 234 only lives 1.2 minutes. In that 1.2 minutes, it then decays to U 234. U 234 has a 250,000 years half-life so after 250,000 years half of that U 234 will have decayed to thorium 230. Thorium 230 has a 75,000 year half-life and decays to radium 226. Radium 226 has a 1502 year half-life. It decays to something called Radon 222. This is the radon that's of consequence of being found in houses and for which radon litigation is sometimes necessary. The radon in houses comes from the fact that there's uranium in the soil and that uranium goes through this decay chain and eventually creates radon. Radon being an inert gas percolates up through the soil and gets into houses or any other space that's put over the soil and floats around inside the house. Now radon 222 lives for 3.8 days so after 3.8 days half of it's gone and it decays to polonium 218. Well, polonium 218 wants to be a solid, not a gas like radon, and so radon decaying into polonium makes the polonium collect into dust particles in the air and those dust particles eventually end up in the walls or the floors or the ceilings or inside your lungs. In your lungs, you see that polonium 218 lives for 27 minutes as a half-life so it has a fair probability of decaying inside of your lungs before it's expelled somehow, by coughing for example. So the polonium 218 undergoes decay and that radioactive decay produces damage inside of your lungs and that's the consequence of radon. The polonium decays to astatine 218 that has a very short half-life of 1.8 times 10 to the minus 4 seconds and so forth. It keeps decaying through this chain; it eventually ends up at lead 206 and lead 206 is stable. It does not decay. So starting from uranium 238 we end up with lead 206. In the process we've made radon which has the potential for being harmful, if in houses.

**Slide #13**

**Curve of Binding Energy**

- Binding energy is the amount of energy that holds a nucleus together, like rocks trapped in the bottom of a valley
- In terms of binding energy per nucleon, iron is the most stable nucleus, with ~9MeV/nucleon
- All elements lighter than iron will tend to fuse together to make a heavier, more bound nucleus (fusion)
- All elements heavier than iron will tend to split apart to make a lighter, more bound nucleus (fission)

**Audio:**
I spoke earlier about binding energy and I want to elaborate a little bit more on it. Binding energy is the amount of energy that holds a nucleus together and it's sort of a like a rock that's trapped at the bottom of a valley; the rock can't get up that hill. It represents that potential energy that's been stored. If we put this in terms of binding energy per nucleon, that is, if we say, what's the total binding energy that holds a nucleus together and we divide that by the number of neutrons plus protons, we get an average number or binding energy per nucleon. Iron turns out to be the most stable of all nuclei. It is the one that has a binding energy of about 9 MeV per nucleon, the average is 9 MeV per nucleon. All elements that are lighter than iron will tend to fuse together, that is merge together, into a heavier nucleus up to the point that they reach iron. Anything that's heavier than iron tends to want to fall apart until it reaches iron and that process is called fission. So there's this general trend that light nuclei would release energy in the process of fusing and heavy nuclei would release energy in the process of fission. We're going to next look at this same concept graphically.

**Slide #14**

**Curve of Binding Energy**

See: http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

[Image] *Graph depicting Binding energy per nuclear particle (nucleon) in MeV versus Mass number (A)*

**Audio:**
Shown here is the graphical representation of the curve of binding energy I spoke about. This is from the website shown on this slide. So the curve shows that very light nuclei, light mass nuclei, have a binding energy that's low (few MeV) per nuclei and that binding energy increases up until you get to iron which I said was about 9 MeV per nucleon and then the curve drifts downward and the average binding energy per nucleon is less all the way out to uranium, for example. So this means that light nuclei shown on the left where it says "yield from nuclear fusion", if you fuse together nuclei in that mass range, you then gain energy so fusing together light nuclei, like helium or lithium or carbon or oxygen, to create iron gains you energy. We'll see that means we can get energy out of the process of fusion, if we can figure out how to make it happen. On the other hand, heavy elements that are much heavier than iron can split apart, they can fission and in that process they can release energy and end up in a lower energy state. So they like to do that; heavier nuclei like to split apart. So what we find is there's a fourth type of radioactive decay. We talked about gamma decay, alpha decay, and beta decay. Alpha decay,

some of these heavy elements are spitting out an alpha particle and falling down this curve from right to left, but another process can happen called fission and this is the fourth type of decay. That uranium 235 nucleus can split roughly in half and turn into something with two pieces that have an average mass of 115 or so and in the process that releases energy so that's the fission process and we'll be talking about that further.

**Slide #15**

**Fission & Fusion**

- Fusion is the process of two light nuclei merging, for example: $^{2}H+^{2}H\rightarrow^{4}He$
- Fusion occurs in stars
- Fission is the process of a heavy nucleus splitting, for example: $^{235}U\rightarrow^{90}Rb+^{143}Cs+2n$
- Fission occurs spontaneously in nature, in nuclear power plants, and in nuclear weapons
- We are naturally radioactive, with such nuclei as $^{40}K$ and $^{238}U$ at the part per million level
- Fission and fusion have had a significant societal impact

**Audio**

So let me elaborate on fission and fusion. Fusion is the process of two light nuclei merging. For example, H 2 plus H 2 goes to helium 4. H 2 is the form of hydrogen that has one proton and one neutron; it's also called deuterium. So this is two deuterium nuclei fusing together to get one helium 4 nucleus. That's fusion. That process occurs in stars, for example. Fusion is the process in stars which generates energy. Fission is the process of a heavy nucleus splitting apart. For example, U 235 can split into rubidium 90 plus cesium 143 plus two neutrons; it's the plus two neutrons that's the important part. The uranium can split up into many possible different combinations of daughter nuclei, that's what the rubidium and cesium are called-daughters. Uranium can fall apart into many different daughters, but, in general, it also spits out some neutrons in the process: two neutrons, one neutron, three neutrons, maybe even four neutrons. Those neutrons we will see are of consequence. We'll come back to them. Fission occurs spontaneously in nature; it's one of the processes that occasionally occur. Sometimes the uranium nucleus just fissions on its own. You can induce fission though; you can cause it to occur. This is what Leo Szilard figured out, producing the chain reaction. We'll talk about. But if you can make fission occur, you can use that to power a nuclear power plant or to provide the energy for a nuclear weapon. One of the things we have to realize is that we are naturally radioactive. We contain nuclei of potassium 40 and uranium 238 and thorium 232 and others. All of these things are at the part per million level inside of our body. They got there from the food we eat, the air we breathe, the things we are exposed to everyday so we contain these elements in our body at small quantities and those materials are radioactive and they decay and that process that occurs inside of us causes some damage to our bodies. We'll talk about that again a little bit later in the next lecture. So fission and fusion have a significant societal impact because they can be the sources of energy for peaceful uses, like nuclear power, or they can be the source of energy for weapons of mass destruction.

**Slide #16**

**Stellar Evolution**

- Stars are powered by nuclear fusion, initially burning hydrogen into helium

- Once the hydrogen is gone, they burn helium into carbon, and then heavier elements up to iron
- At the end of the fusion chain, stars either collapse into brown dwarfs, or if heavy enough, they nova
- In a supernova, all nuclei heavier than iron are created
- The sun will swell to a red giant and then collapse to a brown dwarf

**Audio:**

I mentioned that stars generate energy by nuclear fusion. Stars start off by being highly rich in hydrogen; hydrogen is the most prevalent element in the universe. So stars are made up largely of hydrogen initially and the fusion of hydrogen leads to the production of helium so after a very long time, the helium builds up to large quantities. Now if you look at our sun, our sun is mostly hydrogen still; it's been around for 5 billion years or so. It's going to last for maybe another 10 billion years. It's burned maybe a quarter of the hydrogen and helium so far, but it's still burning hydrogen and will continue to do so in this fusion process, releasing that binding energy that's obtained from that process, but once all the hydrogen is gone the star will collapse farther into itself. Gravity will pull it together and that will tend to make the core hotter and at that point, helium can then start fusing into carbon. Three helium atoms, three helium nuclei can fuse to make one carbon 12 nucleus and so stars that are a little bit later in their life burn helium into carbon and they also tend to produce oxygen by adding another helium nucleus to carbon and nitrogen and a few other elements and as they get older and older and burn more of their helium, they start to burn more and more until they finally are burning materials all the way up to iron, but as I've shown the binding energy curve turns over around iron so once a star has converted a lot of its mass to heavy things up close to iron it can no longer generate enough energy to keep itself from collapsing in. So the star tends to collapse farther and if the star is a light mass star, it may just fall in and become a brown dwarf and that's sort of the end of it. On the other hand, if the star is heavy enough, it will tend to go through other phases. Our sun will go through a series of phases; it will become a red giant and it will fall until it eventually becomes a brown dwarf, but starts that are even heavier can undergo a cataclysmic process called a nova. In the nova or supernova process, related processes, the star collapses in and then in a huge explosion expands out and releases a massive amount of energy. The massive amount of energy is produced in a series of nuclear reaction processes that create all the other, heavier elements than iron. So all of the things that are heavier than iron, like uranium and platinum and gold and silver, all of these things were produced in supernova of stars. So in order for us to be around and the earth to be around, we are made up of the material that was coming from the explosion of stars that lived earlier in our universe. The supernova process creates tremendous amounts of these heavy materials that are then available as a resource to build other stars and to build planets, for example. So we are literally made out of star stuff, the exploding remnants of supernova.

**Slide #17**

**Topics for this Lecture**

Topics for This Lecture

- Properties of nuclei
- History of nuclear physics
- Nuclear model

- Nuclear mass
- $E=mc^2$
- Radioactivity
- Decay chains
- Curve of binding energy
- Fission and fusion
- Stellar evolution

**Audio:**
In this lecture, we've looked at nuclear physics: the properties of nuclei, the history of nuclear physics, nuclear models, nuclear masses, the consequences of $E=mc^2$, radioactivity, decay chains, the curve of binding energy, the fission and fusion process, and finally stellar evolution.