Nuclear Physics: Crash Course Physics #45

Crash Course: Physics
https://youtube.com/watch?v=lUhJL7o6_cA
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(0:03) $E=mc^2$. You hear it all the time, but what does it mean? During his study of special relativity, Albert Einstein found that mass and energy are equivalent, that they can be converted back and forth between one another. He described that relationship mathematically, saying that the energy of a particle is equal to its mass times the speed of light squared.

(0:21) This mass energy equivalent is critical to the study of nuclear physics - the study of the atomic nucleus. This is the branch of physics that introduces you to two of the four fundamental forces. One in which an element can turn into an entirely different element in just an instant. And one that has allowed us to unleash the incredible energy that's contained inside every atom.

(0:41) *Intro song*

(0:53) Before we can dive into the wonders of nuclear physics, we need to recall a little bit about the thing that makes it all tick, the nucleus. The nucleus of any atom consists of protons and neutrons.

(1:04) The proton is positively charged, while the neutron is electrically neutral, and both particles have nearly the same mass. With the exception of hydrogen, which only has a single proton in its nucleus, every element has both protons and neutrons. Because of this we often refer to the two particles collectively as "nucleons." We can describe how many protons and neutrons are in an atom's nucleus using its atomic and mass numbers.

(1:25) An atomic number is how many protons are in a nucleus, which also determines what element the atom consists of. The mass number, meanwhile, is how many protons and neutrons combined make up the nucleus.

(1:36) So, if there are six protons and six neutrons in a nucleus, then its atomic number would be six, making it a carbon nucleus. And the mass number would be six plus six which is twelve. And if there were six protons and eight neutrons, then it would still be carbon nucleus, but with a mass number of fourteen.

(1:52) Let's put these carbon nuclei in nuclear notation to better show the differences between them. First, we start with the chemical symbol for the nucleus, which is determined by its atomic number. Then on the bottom left of the chemical symbol, we write the atomic number, which will be the same for both carbon nuclei - six. Finally, we write the mass number on the top left to signify how many protons and neutrons there are in the nucleus.

(2:13) So, for our carbon atom with six neutrons we'd take the carbon chemical symbol, a capital 'C', and write the atomic number six in the bottom left, and the mass number twelve in the top left. For the atom with the two extra neutrons, the upper left mass number becomes fourteen.

(2:27) Any two nuclei that have the same atomic number, but different mass numbers, are known as isotopes. With most elements having one isotope that's more common than the others.

(2:36) For instance, 99% of the carbon on the Earth is carbon twelve - carbon with the mass number of twelve. Only a tiny fraction of all carbon on Earth is carbon fourteen, since carbon is most stable when the number of protons equals the number of neutrons.

(2:58) It's important to know the masses of different nuclei, since nuclear interactions are all about mass-energy conversion. To quantify the mass of a nucleus, we use the unified atomic mass unit, written just as a small 'u'. A single neutral carbon atom, for example, equals exactly twelve unified atomic mass units. This means that one unified atomic mass units is equal to 1.665 times 10^{-27} kilograms.

(3:12) OK. Now that we have a notation for describing elements and their isotopes, we can talk about the energy associated with a nucleus and its bonds. The first thing you should know is that the total mass of a stable nucleus is always less than the total mass of the individual protons and neutrons put together.

(3:27) For instance, the mass of a neutral helium atom is 4.00603 unified atomic mass units. But two neutrons and two protons, the component parts of a helium atom, taken together have a mass of 4.032980 unified atomic mass units. That means that the nucleus of a helium atom has 0.03037 unified atomic mass units - less mass than its components parts. How can that be?

(3:53) Well, that difference in mass is equal to an amount of energy, specifically the total binding energy, of the nucleus. That binding energy is how much energy you would have to add to the helium atom in order to break apart its nucleus. The amount of energy required to break up a nucleus into its component particles gets larger as the atomic number increases, with iron having one of the highest binding energies per nucleon. But while the total binding energy still increases for nuclei larger than iron, the binding energy per nucleon in fact decreases. This means that very large nuclei are not held together as strongly as small nuclei.

(4:26) Since binding energy accounts for the missing mass, you can calculate it using, you guessed, $E=mc^2$. Now you might be wondering how a nucleus is held together in the first place. You've got neutral neutrons having no problem getting close one another, but what about all of the positive protons? Shouldn't the repulsive electric force keep them apart?

(4:44) Well, one of the four fundamental forces of physics is the strong nuclear force, an attractive force that acts between protons and neutrons in a nucleus. This strong force is substantial enough to overcome the repulsive force between protons, but it only acts over very small distances, while the electric force acts over longer distances.

(5:03) Since the strong force only works across such tiny distances, larger atoms, with higher atomic numbers, actually require additional neutrons to overcome the electromagnetic force and maintain stability within the nuclei.

(5:14) Those extra neutrons are necessary for atoms with atomic numbers higher than 30 or so, as you can see in this chart relating the number of neutrons to the number of protons in a stable atom.

(5:24) When a nucleus is unstable, it can break down into a more stable state. This decay of unstable nuclei, accompanied by the emission of energetic particles, is known as radioactivity.

(5:34) Natural radioactivity was first discover by Henri-Becquerel, who observed how a chunk of mineral that contained uranium affected a photographic plate that was covered up by paper. Even though the paper was blocking out visible light, the radiation from the uranium penetrated the paper and left its mark on the plate. Later scientists studied such decays and categorized the emitted rays, or particles, into three different groups based on their penetrating power.

(5:56) First, there's alpha decay, which is released when an unstable nucleus loses two protons and two neutrons, becoming a different element in the process. In alpha decay there's a parent nucleus, which is the original unstable nucleus, and it decays into a daughter nucleus and an alpha particle, which is actually just the nucleus of a helium atom. This decay occurs because the parent nucleus is too large, and the strong force is no longer sufficient to hold all the nucleons together.

(6:22) For example, if the parent nucleus is radium, it would decay into radon and emit a single alpha particle. The process of the nucleus changing from one element to another is known as transmutation. Know that the atomic number of radon is just two units less than that of radium, and the mass number is four less than radium.

(6:39) In alpha decays the sum of the atomic and mass numbers are always equal on either side of the equation. But even though those numbers of nucleons add up, remember, mass and energy are equivalent. So the products of this reaction always have less total mass, as measured in unified atomic mass units, than the parent nucleus has. The rest of the mass turned into kinetic energy, and the kinetic energy released in nuclear reactions is what's used to generate nuclear power.

(7:02) The alpha particles have the least penetrating power of the three groups. They're barely able to pass through a piece of paper. The second type of decay that can occur is beta decay. When an unstable nucleus emits a beta particle, which is just an electron, you'll see that whenever an electron is produced, so is a neutrino. A neutrino is a particle with a very small mass that is electrically neutral. Its existence is inferred from the conservation of energy.

(7:26) For example, when a nucleus at rest decays into two fragments, it should give each fragment the same amount of momentum. If the nucleus decayed into a daughter nucleus and an electron, the electron would always have the same momentum and the same energy. But electrons from beta decay have been found to have energies that vary greatly. This suggests that a third particle must be carrying away the rest of the energy. And experiments have confirmed that these tiny neutral neutrinos are responsible for that missing energy.

(7:53) Now a unique part of beta decay is that no nucleons are emitted during the decay process. Instead, one of the neutrons changes into a proton, and to compensate for the change in charge, the neutron emits an electron. And although these electrons come from nuclear decay, they are the same kind of electrons that orbit a standard nucleus.

(8:11) Once a neutron changes into a proton, the nucleus changes from one element to another, again an instance of transmutation. And beta decay is caused by the fourth fundamental force - the weak force. While the strong force acts on nucleons, the weak force alters quarks - the fundamental particles that make up both protons and neutrons. By converting quarks of one type into another, the weak force causes the neutron to turn into a proton. As for their penetrating power, beta particles are typically stopped by a few millimeters of aluminum.

(8:39) The third kind of decay is gamma decay, which is what results when a nucleus emits high powered photons in what are known as gamma rays. This kind of decay usually occurs when a nucleus is in an excited state, which can happen because the nucleus is decaying from a larger form, or because it collided with a high energy particle, among other reasons.

(8:57) But the point is when a nucleus is excited, it wants to transition into a lower energy state, which it can do by releasing a photon. Unlike alpha and beta decay, no transmutation occurs in gamma decay. Instead the excited nucleus just decays into a ground state nucleus and a gamma ray. Gamma rays have the highest penetrating power requiring a large amount of concrete or lead to stop their propagation.

(9:19) And there's so much more we could talk about if we had the time: half lives, radio carbon dating, the basics of nuclear power, just to name a few. But $E=mc^2$, now at least you know what it means and how such tiny objects, such as atoms, can release such enormous power. That's worth ten minutes of your time, right?

(9:37) Today we learned the very basics of nuclear physics, including the atomic number, mass number, and how to use them in nuclear notation. We also discussed binding energy and mass energy equivalents, as well as strong and weak forces. Finally, we discussed the three major types of radioactive decay, alpha, beta, and gamma.

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