



The Big Idea

The nuclei of atoms are affected by three forces: the strong nuclear force which causes protons and neutrons to bind together, the electric force, which is manifested by repulsion of the protons and tends to rip the nucleus apart and the weak nuclear force which causes neutrons to change into protons and vice versa.

The strong force predominates and can cause nuclei of complex atoms with many protons to be stable. The electric force of repulsion is responsible for fission, the breaking apart of nuclei and it is responsible for atom bombs and nuclear power. A form of fission, where a helium nucleus is a product, is called *alpha radiation*. The actions of the weak force give rise to *beta radiation*. A change in nuclear energy can also give rise to *gamma radiation*, high energy electromagnetic waves. Particles that emit alpha radiation, beta radiation, and gamma radiation go through the process of *radioactive decay*, which cause the heating of the molten core of the earth, and has even played a role in the mutations in our evolutionary history. Fission and fusion, the latter where light nuclei combine to form new elements, are accompanied by copious amounts of gamma radiation. These processes often produce radioactive nuclei; in nature these radioactive nuclei were forged in the explosive deaths of ancient stars.

Key Equations

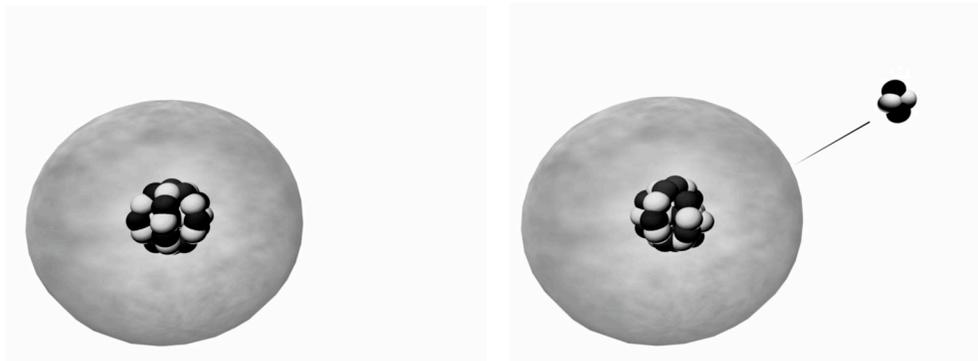
- $N = N_0 \left(\frac{1}{2}\right)^{t/t_H}$; the number N of nuclei surviving after an original N_0 nuclei decay for time t with a half-life of t_H .
- $t = t_H \ln(N/N_0) / \ln(1/2)$; the amount of time t it takes a set of nuclei to decay to a specified amount.
- ${}^A_Z X$; X is the symbol for the element involved; for example (U for uranium); Z is the atomic number and A is the atomic mass number. (The total number of nucleons—protons and neutrons, 235 for uranium.)
- $E = \gamma mc^2$; energy produced when some mass is lost during radioactive decay.
- $N = N_0 e^{-\lambda t}$; the decay equation. λ tells you the decay rate.
- $t_H = \ln 2 / \lambda$; how to convert λ to the half-life value

Key Concepts

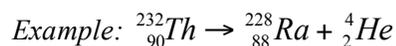
- Some of the matter on Earth is unstable and undergoing nuclear decay.
- Alpha decay is the emission of a helium nucleus, causing the product to have an atomic number 2 less than the original and an atomic mass number 4 less than the original.
- Beta minus decay is the emission of an electron, causing the product to have an atomic number 1 greater than the original
- Beta plus decay is the emission of a positron, causing the product to have an atomic number one less than the original.
- When an atomic nucleus decays, it does so by releasing one or more particles. The atom often (but not always) turns into a different element during the decay process. The amount of radiation given off by a certain sample of radioactive material depends on the amount of material, how quickly it decays, and the nature of the decay product. The measure of how quickly a nucleus decays is given by the *half-life* of the nucleus. Half-life is the amount of time it will take for half of the radioactive material to decay.
- The type of atom is determined by the atomic number (i.e. the number of protons). The atomic mass of an atom is approximately the number of protons plus the number of neutrons. Typically, the atomic mass listed in a periodic table is an average, weighted by the natural abundances of different isotopes.
- The atomic mass number in a nuclear decay process is conserved. This means that you will have the same *total* atomic mass number on both sides of the equation. Charge is also conserved in a nuclear process.
- It is impossible to predict when an individual atom will decay, one can only predict the probability; but predicting when a portion of a macroscopic sample, which contains a vast number of atoms, will decay can be calculated extremely accurately.
- The nuclear process is largely random in direction. Therefore radiation strength decreases with distance by the inverse square of the distance (the $1/r^2$ law, which also holds for gravity, electric fields, light intensity, sound intensity, and so on.)

Key Applications

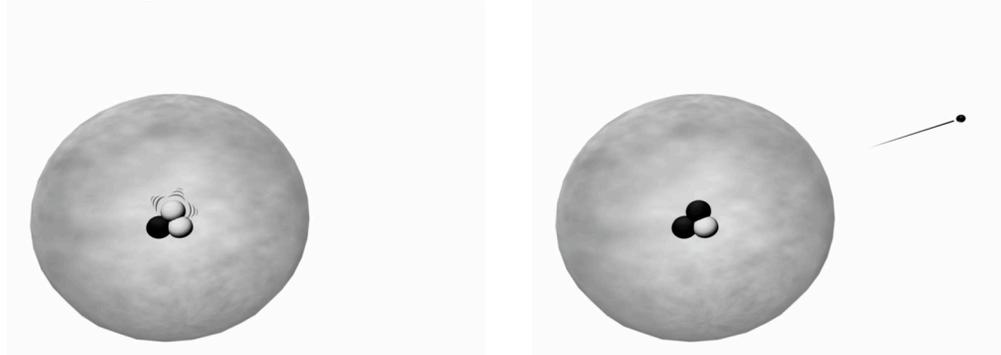
Alpha Decay



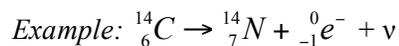
- *Alpha decay* is the process in which an isotope releases a helium nucleus (2 protons and 2 neutrons ${}^4_2\text{He}$) and thus decays into an atom with two less protons.



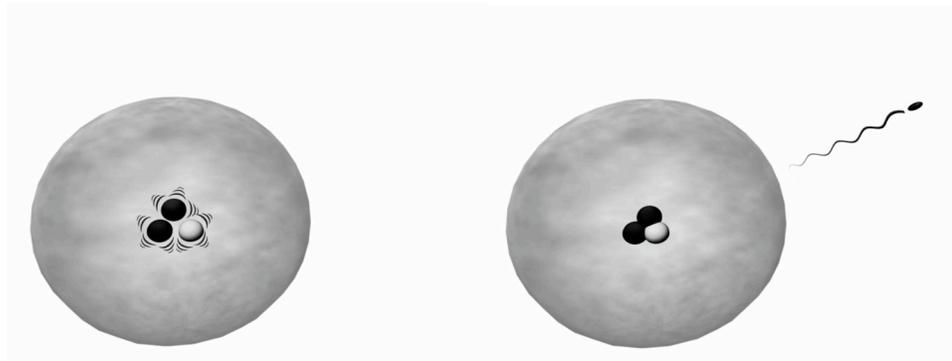
Beta Decay



- *Beta decay* is the process in which one of the neutrons in an isotope decays, leaving a proton, electron and anti-neutrino. As a result, the nucleus decays into an atom that has the same number of nucleons, with one neutron replaced by a proton. (Beta positive decay is the reverse process, in which a proton decays into a neutron, anti-electron and neutrino.)



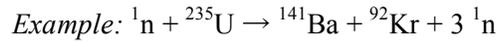
Gamma Decay



- *Gamma decay* is the process in which an excited atomic nucleus kicks out a photon and releases some of its energy. The makeup of the nucleus doesn't change, it just loses energy. (It can be useful to think of this as energy of motion – think of a shuddering nucleus that only relaxes after emitting some light.)



- *Fission* is the process in which an atomic nucleus breaks apart into two less massive nuclei. Energy is released in the process in many forms, heat, gamma rays and the kinetic energy of neutrons. If these neutrons collide with nuclei and induce more fission, then a runaway *chain reaction* can take place. Fission is responsible for nuclear energy and atom-bomb explosions: the fission of uranium acts as a heat source for the Earth's molten interior.



- *Fusion* is the process in which two atomic nuclei fuse together to make a single nucleus. Energy is released in the form of nuclear particles, neutrinos, and gamma-rays.

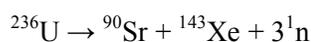


- *Radioactive carbon dating* is a technique that allows scientists to determine the era in which a sample of biological material died. A small portion of the carbon we ingest every day is actually the radioactive isotope ${}^{14}\text{C}$ rather than the usual ${}^{12}\text{C}$. Since we ingest carbon every day until we die (we do this by eating plants; the plants do it through photosynthesis), the amount of ${}^{14}\text{C}$ in us should begin to decrease from the moment we die. By analyzing the ratio of the number of ${}^{14}\text{C}$ to ${}^{12}\text{C}$ atoms in dead carbon-based life forms (including cloth made from plants!), we can determine how long ago the life form died.

Radioactivity and Nuclear Physics Problem Set

1. After 6 seconds, the mass of a sample of radioactive material has reduced from 100 grams to 25 grams. Its half-life must be
 - a. 1 s
 - b. 2 s
 - c. 3 s
 - d. 4 s
 - e. 6 s

2. Which of the following is true for the following reaction?



- a. This is a fission reaction.
 - b. This is a fusion reaction.
 - c. This is not a valid reaction, because the equations don't balance.
3. For any radioactive material, its half-life...
 - a. ...first decreases and then increases.
 - b. ...first increases and then decreases.
 - c. ...increases with time.
 - d. ...decreases with time.
 - e. ...stays the same.
 4. If the half-life of a substance is 5 seconds, it ceases to be radioactive (i.e. it ceases emitting particles), ...
 - a. ... after 5 seconds.
 - b. ... after 10 seconds
 - c. ... after 20 seconds.
 - d. ... after a very long time.
 5. You detect a high number of alpha particles every second when standing a certain distance from a radioactive material. If you triple your distance from the source, the number of alpha particles you detect will decrease. By what factor will it decrease?
 - a. $\sqrt{3}$
 - b. 3
 - c. 9
 - d. 27
 - e. It will stay the same.

6. You have 5 grams of radioactive substance A and 5 grams of radioactive substance B. Both decay by emitting alpha-radiation, and you know that the higher the number of alpha-particles emitted in a given amount of time, the more dangerous the sample is. Substance A has a short half-life (around 4 days or so) and substance B has a longer half-life (around 10 months or so).
 - a. Which substance is more dangerous right now? Explain.
 - b. Which substance will be more dangerous in two years? Explain.

7. Write the nuclear equations $A \rightarrow B + C$ for the following reactions.
 - a. The alpha decay of ^{219}Ra .
 - b. The beta decay of ^{158}Eu .
 - c. The beta decay of ^{53}Ti .
 - d. The alpha decay of ^{211}Bi .

8. A certain radioactive material has a half-life of 8 minutes. Suppose you have a large sample of this material, containing 10^{25} atoms.
 - a. How many atoms decay in the first 8 minutes?
 - b. Does this strike you as a dangerous release of radiation? Explain.
 - c. How many atoms decay in the second 8 minutes?
 - d. What is the ratio of the number of atoms that decay in the first 8 minutes to the number of atoms that decay in the second 8 minutes?
 - e. How long would you have to wait until the decay *rate* drops to 1% of its value in the first 8 minutes?

9. There are two equal amounts of radioactive material. One has a short half-life and the other has a very long half-life. If you measured the decay rates coming from each sample, which would you expect to have a higher decay *rate*? Why?

10. Hidden in your devious secret laboratory are 5.0 grams of radioactive substance A and 5.0 grams of radioactive substance B. Both emit alpha-radiation. Quick tests determine that substance A has a half-life of 4.2 days and substance B has a half-life of 310 days.
 - a. How many grams of substance A and how many grams of substance B will you have after waiting 30 days?
 - b. Which sample (A or B) is more dangerous at this point (i.e., after the 30 days have passed)?

11. The half-life of a certain radioactive material is 4 years. After 24 years, how much of a 75 g sample of this material will remain?

12. The half life of ^{53}Ti is 33.0 seconds. You begin with 1000 g of ^{53}Ti . How much is left after 99.0 seconds?

13. You want to determine the half-life of a radioactive substance. At the moment you start your stopwatch, the radioactive substance has a mass of 10 g. After 2.0 minutes, the radioactive substance has 0.5 grams left. What is its half-life?
14. The half-life of ^{239}Pu is 24,119 years. You have 31.25 micrograms left, and the sample you are studying started with 2000 micrograms. How long has this rock been decaying?
15. A certain fossilized plant is 23,000 years old. Anthropologist Hwi Kim determines that when the plant died, it contained 0.250 g of radioactive ^{14}C ($t_H = 5730$ years). How much should be left now?
16. A young girl unearths a guinea pig skeleton from the backyard. She runs a few tests and determines that 99.7946% of the original ^{14}C is still present in the guinea pig's bones. The half-life of ^{14}C is 5730 years. When did the guinea pig die?
17. You use the carbon dating technique to determine the age of an old skeleton you found in the woods. From the total mass of the skeleton and the knowledge of its molecular makeup you determine that the amount of ^{14}C it began with was 0.021 grams. After some hard work, you measure the current amount of ^{14}C in the skeleton to be 0.000054 grams. How old is this skeleton? Are you famous?
18. Micol had in her lab two samples of radioactive isotopes: ^{151}Pm with a half-life of 1.183 days and ^{134}Ce with a half-life of 3.15 days. She initially had 100 mg of the former and 50 mg of the latter.
 - a. Do a graph of quantity remaining (vertical axis) vs. time for both isotopes on the same graph.
 - b. *Using the graph* determine at what time the quantities remaining of both isotopes are exactly equal and what that quantity is.
 - c. Micol can detect no quantities less than 3.00 mg again *using the graph* determine how long she will wait until each of the original isotopes will become undetectable.
 - d. The Pm goes through β^- decay and the Ce decays by means of electron capture. What are the two immediate products of the radioactivity.
 - e. It turns out both of these products are themselves radioactive; the Pm product goes through β^- decay before it becomes stable; the Ce product goes through β^+ decay before it reaches a stable isotope. When all is said and done what will Micol have left in her lab?

