Nuclear Energy: Nuclear Decay

Introduction

The Nucleus

Almost any phrase that has the word “nuclear” in it has a bad reputation. The term conjures up images of mushroom clouds and radioactive mutants. It is interesting to note that in the 1940’s and 50’s, the term that applied to energy derived from the decay radioactive material was atomic energy. This term was somewhat correct, since the energy was coming from the breakdown of the atom. It was not until later that the more appropriate term nuclear energy was used as more people began to understand that the energy was coming from the breakdown of the nucleus of the atom.

The picture at the right is a popular image of the atom. While not a true depiction of the appearance of a real atom, it does mirror most of the features of it, such as a central nucleus composed of positively-charged protons and neutrally-charged neutrons that is orbited by negatively-charged electrons. The classic approach to discussing the atom is to tell students that it is held together by electrostatic attraction between the protons and electrons. But this is only part of the picture. What rarely gets discussed is what is holding the nucleus together, as there is not electrostatic force whatsoever holding the protons to the neutrons.

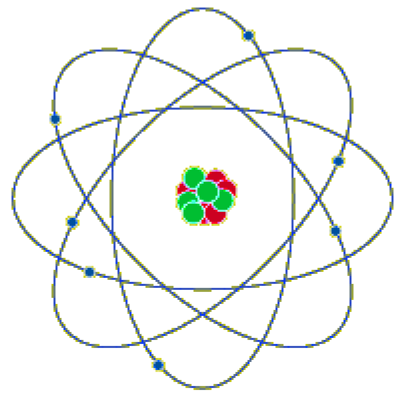


Figure 1: Simplified diagram of an atom

The forces that are binding the neutrons to the protons are the strong and weak nuclear forces. Unlike the electrostatic force, which is relatively simple to explain (like charges repel and unlike attract), the strong and weak nuclear forces are rather complicated in that the discussion of them involves quarks, gluons, and vector bosons and their interactions. However, intimate knowledge of these forces is not required in order to understand nuclear energy, and therefore, we will leave it to the reader to research this subject as they desire. For the purposes of this discussion, we will merely note that the forces do exist, that they are important over very short distance scales (10^{-15} m and less), and that they bind neutrons to protons under certain conditions.

Isotopes

If an atom is to be neutral, it must have the same number of electrons as it does protons, i.e. the total amount of negative charge must equal the total amount of positive charge (elements are defined by the number of protons in the nucleus). Is there some type of rule like this that applies to the number of neutrons that an atom has? It turns out that the answer is “No”. The complicated nature of the strong and weak nuclear forces plus the numerous configurations that could be used for storing protons and neutrons in a nucleus means that there is no given rule for the numbers of neutrons an element has. In fact, most elements have multiple numbers of neutrons that can be stored in the nucleus. Atoms that have the same number of protons, but different numbers of neutrons, are known as **isotopes** of an element.

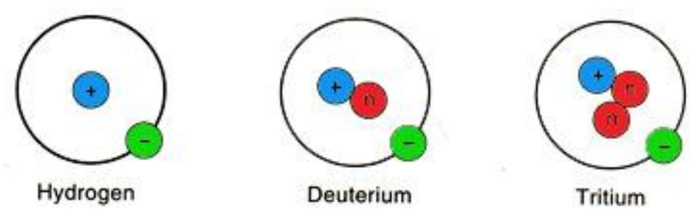


Figure 2: Bohr models of hydrogen, deuterium, and tritium

Not all of these isotopes are stable. For most naturally occurring elements, there is at least one isotope that is stable. The picture to the left shows three different isotopes of hydrogen. The first of these, which is what we normally think of as hydrogen, is called hydrogen-1 and is stable. The other two isotopes are called hydrogen-2 (deuterium) and hydrogen-3 (tritium). Deuterium, which is found in nature in about 1 in every 6500 atoms of hydrogen, is stable, whereas tritium, which is much rarer, is unstable and will undergo radioactive decay, if given enough time. Other examples of isotopes with which you might be familiar are carbon-12 (6 protons and 6 neutrons), which is stable, and carbon-14 (6 protons and 8 neutrons), which is unstable. Carbon-14 is one of the radioactive isotopes that is used to determine the age of biological fossils. There are some elements for which there are no stable isotopes. An example of this would be uranium. If given enough time, all forms of these elements will decay.

Isotopes of a particular element behave the same chemically. That is to say, molecular compounds that can be made with one isotope of an element can be made in the same way with any other isotope of that same element. For example, water (H_2O) can be constructed using hydrogen-1, hydrogen-2 (deuterium), or hydrogen-3 (tritium). The water molecules made from each of these will all look, taste, and feel like water. The only physical difference between them will be that water molecules made with deuterium and tritium will be heavier and denser than the one made with hydrogen-1. The one made with tritium will differ in one other way: they will also be radioactive.

Radioactive Decay

Methods of Decay

When an atom decays, it can do so via one of three natural methods. These methods are known as alpha, beta, and gamma. In alpha decay, the unstable nucleus ejects an alpha particle, which is composed of two neutrons and two protons. Another way of stating this is that the nucleus decays by ejecting a helium-4 nucleus. In beta decay, the nucleus ejects a beta particle, which is either an electron (beta minus) or a positron (beta plus). At first glance, this would seem to be wrong, as a nucleus is comprised of protons and neutrons and contains no electrons or positrons. But they are produced in the nucleus whenever a neutron decays into a proton, an electron, and a neutrino or a proton decays into a neutron, a positron, and a neutrino. The last way of decaying is via gamma decay, which is when electromagnetic radiation is given off by the nucleus as the protons and neutrons become more tightly bound.

There is another way for a nucleus to decay, though this method usually involves the actions of humans. A nucleus can be forced to break apart if it is hit by particles from outside of the nucleus. This was discovered by Ernst Rutherford in the early 1900’s when he bombarded nitrogen-14 (7 protons, 7 neutrons) with alpha particles (helium-4) to produce oxygen-17 (8 protons, 9 neutrons) and a proton. The easiest method for doing this type of decay is to bombard the nucleus with neutrons. Since the neutrons have no net charge, they are not repelled electrostatically away from the nucleus like a proton would be, and thus, do not require large energies in order to strike it. This will be important in our next activity, where we discuss the operation of a nuclear power plant.

Half-Life Versus Activity

If left on their own, unstable isotopes will decay in an exponential fashion. That is, given a large enough quantity of an isotope, the same percentage of them will decay in the same amount of time. This means that in a given year, the number of isotopes that decay, divided by the original number of isotopes, will be the same quantity. Rather than listing this fraction for isotopes, though, we often turn the issue on its head and discuss the length of time it takes for a certain fraction of the material to decay. In particular, we list the amount of time that it takes for half of the isotopes to decay, which is called the half-life of the substance. For example, iodine-131 has a half-life of 8 days. If one were to start with 100 kg. of it, after 8 days, they would only have 50 kg. After another 8 days, they would have 25 kg left, and so on and so forth. Eventually, the amount of iodine-131 would become so small that it would no longer obey exponential decay, at which time we would have no way of determining when a particular amount of the substance would decay.

This is not to imply, though, that the fraction of the substance that will decay in a given time period is not important. It is very important, as this quantity is related to the activity, which is the number of decays that occurs per unit time. It is just that the activity and the half-life are inversely related, which means that knowledge of the half-life allows one to calculate the activity using the equation

Activity = .69*number of isotopes/half-life

While the half-life gives you some indication of how long a radioactive substance will be around, the activity tells you how much radiation it is currently emitting. This relationship often confuses people. For instance, a lot of people will look at a substance that has a half-life of a billion years as a bad thing. They fixate on how long the substance will be around. However, a very long half life is a good thing from a radiation standpoint, as it means that you would need an enormous quantity of the substance in order for there to be any appreciable activity. Another way to think of it is that stable isotopes, the substances that are not radioactive, have an extremely long half-life; it is infinite.

Before we proceed to the activity, there is one last thing that we need to clarify. When a substance decays, it does not disappear. The nucleus does lose energy, and possibly some particles, but there is still at least one nucleus left after the decay. For instance, in the example above, the iodine-131 that decays will most likely decay into xenon-131, which is stable. But what if the substance that a radioactive isotope decays into is itself radioactive? The chart at the right shows a possible radioactive decay chain for uranium-238. As you can see, the uranium-238 decays into thorium-234, which is radioactive and decays into protactinium-234. The isotopes that result keep being radioactive until lead-206 is reached, at which point the decaying stops. This is one of the primary problems with radioactive waste from a nuclear reactor. The material stays active for a long period time, with both long and short half-life isotopes, as a succession of radioactive materials is produced and decayed.

Isotope	Half-life	Decay mode
Uranium-238	4.5 billion years	alpha
Thorium-234	24.1 days	beta, gamma
Protactinium-234	1 minute	beta, gamma
Uranium-234	245,000 years	alpha, gamma
Thorium-230	76,000 years	alpha, gamma
Radium-226	1,600 years	alpha, gamma
Radon-222	3.8 days	alpha
Polonium-218	3.0 minutes	alpha
Lead-214	27 minutes	beta, gamma
Bismuth-214	20 minutes	beta, gamma
Polonium-214	160 microseconds	beta, gamma
Lead-210	22 years	beta, gamma
Bismuth-210	5 days	beta, gamma
Polonium-210	138 days	beta, gamma
Lead-206	stable	

Figure 3: U-238 decay chain, in descending order of daughter products

Internet Exercises

Half-life

The following link will open up a new window that contains an interactive Java applet that simulates the decay of a quantity of radioactive isotopes into daughter products. As this decay occurs, the applet plots the activity (energy released) and the number of radioactive isotopes left. Some of the sample isotopes decay directly into stable daughters; some decay into unstable daughters that then decay into stable isotopes. In particular, try using carbon-10, carbon-15, oxygen-20, oxygen-22, and fluorine-23 in the simulation, and note the concentrations and activity levels as the decays proceed.

Decay Chains

The next link opens up a new window that contains an interactive Java applet that shows possible decay chains for most known isotopes. Note that some isotopes have more than one decay chain, such as uranium-238. Isotopes that might be of particular interest are hydrogen-3 (H-3), carbon-14 (C-14), radon-222 (Rd-222), uranium-235 (U-235), and uranium-238 (U-238). Note the number of daughter products that are produced from each of these. Is there a general difference between the lighter and heavier isotopes?

Laboratory Exercises

Dice

While it would be nice to do an actual decay experiment with radioactive materials, the idea of doing so gives many people the willies (and, quite possibly, the heeby-jeebies). A decay experiment would require a safe storage facility on campus, enough safety and monitoring equipment to outfit both students and instructors, and time in the course to cover proper safety procedures, amongst other things. The time, money, and equipment needed to do this is just too much for most institutions

This does not mean, though, that we cannot study the behavior of radioactive isotopes. As we said before, the decay of isotopes is a random process (we never know when any one isotope will decay) that follows very well studied group statistics (the same percentage of materials will decay over equal amounts of time). This process can be mirrored very nicely by another random event that follows well-known statistics: dice rolling. In a large group of dice that are thrown, no one can state for certain that a particular die will come up with a 1 or a 6 on it. However, one can say that the same percentage of dice in the whole group should come up with the same number, on average.

Figure 4: Six-sided dice

For this activity, we will need two groups of different colored dice or cubes. These two colors will correspond to two different radioactive isotopes. For purposes of discussion, we will call one color Group A and the other Group B. You should have a large number of each group, with 100 dice or cubes being a good target. For Group A, designate one side of each die or cube as the decay side, i.e. when this side comes up during a roll, the die or cube is considered to have decayed. Group B should have 2 sides designated. For example, if you use dice, you could designate 1 as the decay side in Group A and 2 and 3 as the decay sides for Group B. To make it easier to notice these sides when you are doing the activity, you might want to mark the decay sides with paint or ink.

Because the dice or cubes are six-sided, the odds of any member of Group A "decaying" is 1 in 6; the odds for any member of Group B, 1 in 3. Therefore, each roll of the Group A should see have an activity that is $1/6^{th}$ of the total number of members rolled, while each roll of Group B should have an activity that is $1/3^{rd}$ of the total number of members.

Part A

Once you have the two groups acquired and a bucket or container into which to place them for throwing, you are set to begin. Start with all of the members of Group A in your container. Roll them all at once, and then pick out all of the dice or cubes that have turned up with their decay side. Count and record the number of these on your activity sheet, and place all of the remaining members of Group A back into the container. Roll them all again, repeating the above procedure of counting, recording, and removing "decayed" members until you have no more dice or cubes left. Repeat this exact same procedure with Group B. When you have completed both groups, plot your results on the diagrams on the Activity Sheets.

Part B

In Part B, we consider the case of a daughter product being radioactive itself. This time, when our initial cubes or dice “decay”, we will replace them with cubes from the other group and continue. This is equivalent to saying that Group A decays into Group B, which decays into something stable.

First, let us start with all members of Group A in the container. We roll these, and then separate out the members of A that have “decayed”. We count and record this number, and then add exact same number of cubes or dice from Group B into the mix. We now roll these, and separate out the members from A that have “decayed” and the members of B that have “decayed”. We record the number of both. For all of the Group A dice or cubes that have “decayed”, we remove them and replace them with an equal number of members from Group B. All of the members of group B that have decayed, though, get removed from the mix permanently. We keep doing this until we have no Group B members left in the container. For example, if we roll 100 dice from Group A the first time and 16 of them have their decayed side up, we remove those 16 Group A dice and replace them with 16 Group B dice. We then roll these 84 Group A and 16 Group B dice. Supposed 13 Group A and 5 Group B dice have their decayed side up. We then remove the 5 Group B dice permanently, and replace the 13 Group A dice with 13 Group B dice.

After we have completed this, we then repeat the procedure with Groups A and B switched, i.e. we start with all Group B dice or cubes and replace each of them with Group A when they decay. Upon finishing this, we will plot our results on the diagrams on the Activity Sheets.

ESA21: Environmental Science Activities

Activity Sheet
Nuclear Decay

Name:
Lecture Professor:

Part A:

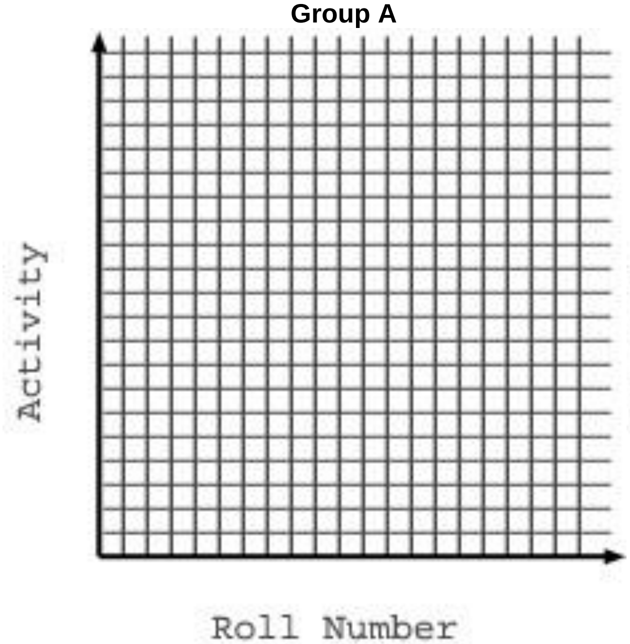
Group A

Roll No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Remaining																				
Decayed																				

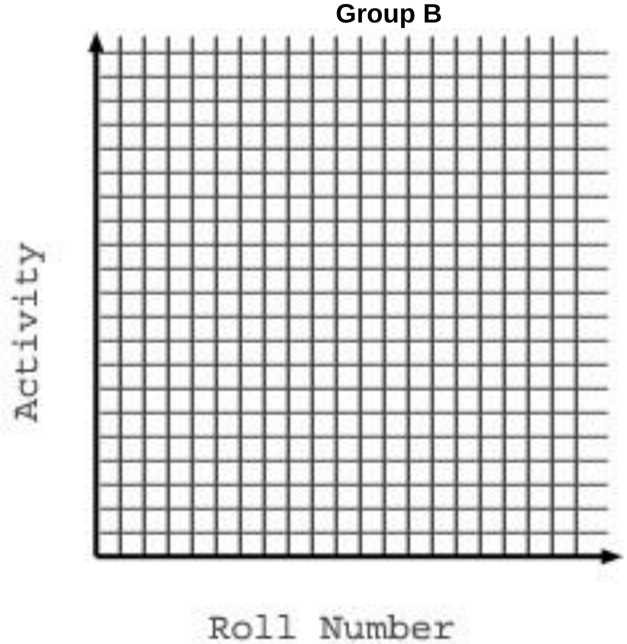
Group B

Roll No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Remaining																				
Decayed																				

Group A



Group B



1. How does the activity of each group correspond to your expected results?

2. From the tables above, you should be able to estimate a “half-life” for each group by noting how many rolls it takes for half of the members to “decay”. Which has a longer half-life, A or B? Did you expect this?

Part B:

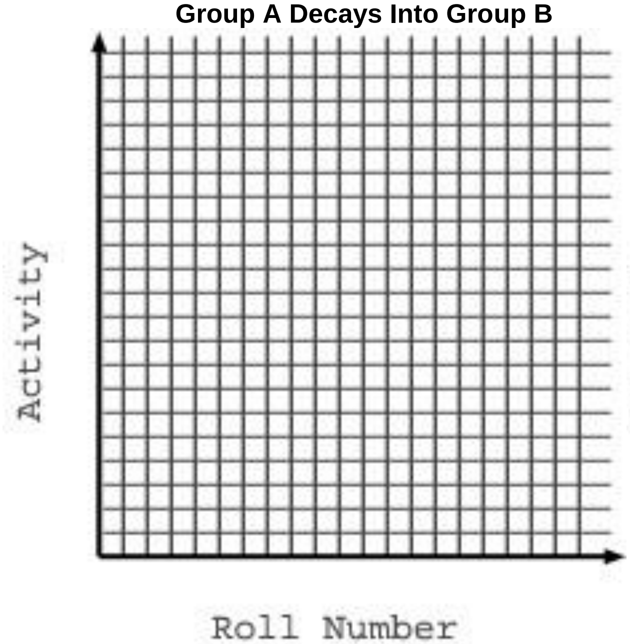
Group A Decays Into Group B

Roll No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A Decay																				
B Decay																				
Total																				

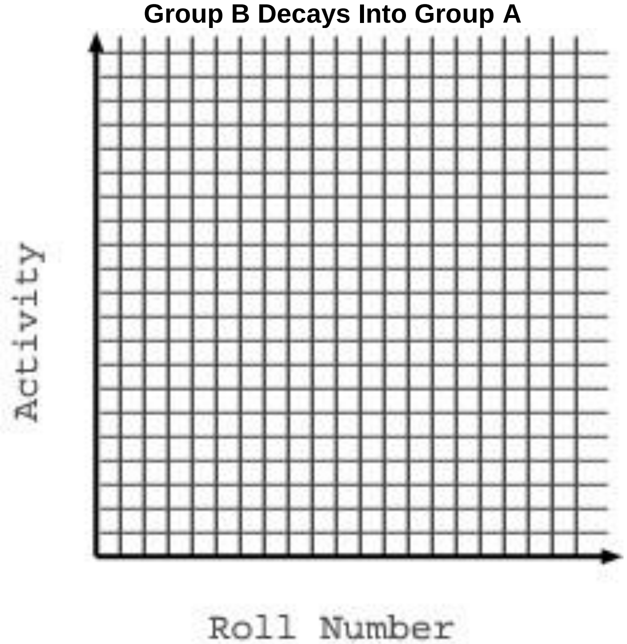
Group B Decays Into Group A

Roll No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
B Decay																				
A Decay																				
Total																				

Group A Decays Into Group B



Group B Decays Into Group A



3. Which configuration had the higher activity: Group A decaying into Group B, or vice versa? Is this what you expected? Why?