Chapter 14 Notes: Nuclear Structure and Radioactivity

What happens when atomic nuclei are transformed by "radioactive decay"?

In Chapter 13 we discussed the electrons in the atom, but we did not say anything regarding the atomic nucleus. There are no electrons in the nucleus and, by comparison to the amount of space occupied by the electrons, the nucleus is extremely tiny. Nonetheless there are powerful forces at work in the nucleus, and as a result many important phenomena have their origins there.

Structure of the Nucleus: The nucleus [plural: *nuclei*], which is the "core" of the atom, is composed of particles called "nucleons," of which there are two types:

(1) ***protons*** (positively charged); the number of protons in a nucleus is called the ***"Atomic Number"*** [symbol: Z], and identifies which element corresponds to that particular nucleus.

(2) ***neutrons*** (no electric charge); the number of neutrons in a nucleus is called the "neutron number."

Different ***isotopes*** of a single element all have the same Z, but different numbers of neutrons.

The nucleons are held together by the ***"strong"*** force, which is also called the "nuclear" force. This is the strongest force known in nature – about 100 times stronger than the electromagnetic force. The reason that we are not normally aware of its presence is that it has a very short range: its effects are only significant over distances smaller than about 10^{-15} m. The nucleus itself is approximately 10^{-14} m in diameter (larger for nuclei with more protons), while the diameter of an atom is much larger: approximately 10^{-10}m.

It is the powerful nuclear force that keeps the protons in the nucleus bound tightly together; without it, repulsive electrical forces would push the protons far apart. Instead of the different parts of the nucleus breaking apart on their own, a great deal of ***external*** energy is required to disassemble a nucleus. The source of ***nuclear energy*** is the strong nuclear force; this energy can be released in processes such as "fission" (the splitting of a nucleus into two parts) and "fusion" (the joining of two nuclei to form one larger one).

The "ordinary" state of an atom is to be electrically neutral; in that case, the number of electrons must equal the number of protons. (Atoms may also exist as ***ions;*** in that case, there are more or fewer electrons than there are protons.) It is the electrons – their number and their arrangement in the atom – that determine the ***chemical*** properties of the atom. For that reason, the atomic number Z – which is equal to the number of protons – determines the chemical properties of the neutral atom. Thus, different elements – each of which has a different value of Z – have different and distinct chemical properties.

Radioactive Decay: Certain types of nuclei are said to undergo radioactive "decay" when they transform into another type of nucleus. (Nuclei that decay are said to be "unstable.") The transformation, or decay, is accompanied by emission of certain types of particles ("alpha" and "beta" particles), or of a gamma ray. An ***alpha particle*** is composed of two neutrons and two protons bound together; it is identical to the nucleus of a helium atom. A ***beta particle*** is actually just an electron; this electron is *produced* by certain types of nuclear interactions, and is not a permanent component of the nucleus. The gamma rays that are emitted during radioactive decay are high-energy electromagnetic photons; they are produced when the nucleons *drop* from one energy level to a lower one. (Just as the electrons in an atom have certain specific energy levels, so too do the nucleons.)

Radioactivity – the decay of unstable nuclei and the accompanying emission of particles and gamma rays – has many important practical uses. Radioactive materials are used as "tracers" for medical diagnosis, and they are also used for therapeutic purposes (such as the destruction of malignant tumors). Radioactivity can also be used to find the ages of both biological materials and geological samples. With these methods, ages up to several billion years can be reliably determined.

It is not possible to determine when one particular unstable nucleus will decay. However, it ***is*** possible to determine to a very high degree of accuracy what proportion of a ***very large sample*** of unstable nuclei of any given type will decay each second. For instance, if we have 1000 nuclei of type "A," we might find that 4% of them will decay each second. (We will assume here that they each decay into a single nonradioactive nucleus.) In this example, we would find that of the original sample of 1000 nuclei, 40 of them will decay in the first second. For ***any other sample*** consisting of 1000 nuclei of type "A", we can be confident that very close to 40 of them will decay in one second. We would say that the ***"decay constant"*** of this particular nucleus is 4%/s [four percent per second]. Using the symbol "λ" for decay constant, we would say that $\lambda = 0.04$/s for this nucleus. [We can also write this as $\lambda = 0.04\ s^{-1}$].

Some symbols we will use:

N: number of radioactive nuclei of a given type present at a particular moment in time. N is a function of time: $N = N(t)$.

λ ["decay constant"]: fraction of nuclei present which decay per unit time. ***Note that in this context, λ does <u>not</u> represent a wavelength!*** If we express λ in units of s^{-1}, we have this important relationship:

$$\boxed{\textbf{decays per second} = \lambda \boldsymbol{N}}$$

n: number of radioactive decays [and so we have: *number of decays per unit time* $= n/\Delta t$]

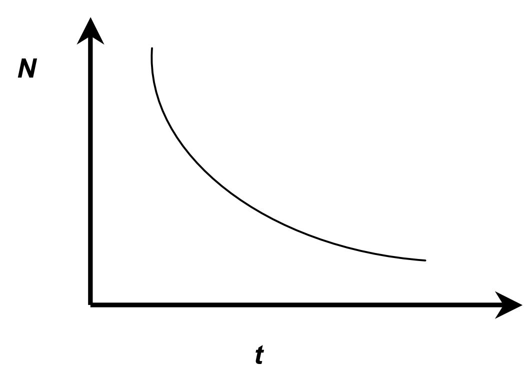
ΔN: change in value of N. [A ***decrease*** in N would correspond to a ***negative*** value of ΔN.]

If there are "n" decays in time Δt, the value of N will ***decrease*** by n. Therefore, we can see that: $\dfrac{\Delta N}{\Delta t} = \dfrac{-n}{\Delta t} = -\lambda N$

[This equation leads to the following mathematical expression for $N(t)$: $N = N_{initial}\, e^{-\lambda t}$]

If a certain number of radioactive nuclei are collected together, some of them will decay each second. Ordinarily, they decay into a single nonradioactive nucleus. (This is the situation we will consider here.) Therefore, as time goes on, the number of radioactive nuclei remaining declines. What stays the ***same***, however, is the decay constant λ; that is a property of that type of nucleus, and is unrelated to the number of such nuclei that are present.

Because the decay constant does not change, the ***fraction*** of the radioactive nuclei that decay each second does not change. But that is not the fraction of the ***original*** number of nuclei – it is the fraction of the number present at any given moment. That is, the number of decays per second is equal to λN. So, if $\lambda = 0.03$/s, 3% of the radioactive nuclei present – call this number "N_1" – will decay in one second. But then, after that one second, there are ***fewer*** radioactive nuclei present; call that new number "N_2"; 3% of $\boldsymbol{N_2}$ will decay in the ***next*** second. (The ***total*** number of nuclei – radioactive plus nonradioactive – remains constant, according to our assumptions here.) For this reason, the number of decays per second declines in direct proportion to the number of radioactive nuclei present. Because the number that decay each second gets smaller as time goes on, the rate of decrease of radioactive nuclei itself decreases. This leads to a graph of N that decreases as a function of time – but not in a straight line. Rather, the graph is curved, and looks something like this:



The time required for a given sample of radioactive nuclei to decrease in number by 50% is a characteristic property of each type of nucleus. It is related to the decay constant, and so does not vary when the number of nuclei present changes. This time is called the "half-life" [symbol: $T_{1/2}$]; it is inversely related to the decay constant. (A larger decay constant corresponds to a ***smaller*** half-life.)

Radioactive Dating: Radioactive materials are often used to provide estimates of the ages of substances that contain those radioactive materials. A particularly important example is ***radiocarbon dating*****,** which makes use of the radioactive nucleus ^{14}C that has a half-life of 5730 years. (The number "14" refers to the total number of nucleons – protons [6] plus neutrons [8] – in this nucleus. The nonradioactive form of carbon is ^{12}C, and has 6 protons and 6 neutrons.)

The relative proportions of ^{14}C and ^{12}C in the atmosphere have been fairly stable for the past 50,000 years or so. In a sample of 10^{12} nuclei, approximately *one* will be ^{14}C, and the rest will be ^{12}C. Plants absorb carbon (in the form of carbon dioxide) from the air and animals eat plants. As long as the organisms are alive, the ratio of ^{14}C to ^{12}C in their tissues remains at the atmospheric ratio of 1 in 10^{12}. However, when the organism dies, the radioactive carbon is no longer replenished from the atmosphere and so its proportion *decreases*. By measuring the relative proportions of the two types of carbon in a sample of biological material, the age of the sample can be determined with great accuracy (up to approximately 50,000 years).

For instance, suppose a sample of material is examined in which only one ^{14}C nucleus is present for every 4×10^{12} ^{12}C nuclei. This is only ¼ of the usual ratio. It must be that the rest of the ^{14}C nuclei which were originally present have decayed away. Now, it takes 5730 years – one half-life – for the number of ^{14}C nuclei to decrease by half. That is, we started out with a concentration of ^{14}C nuclei that was equal to *one* in 10^{12}; after 5730 years have elapsed, that concentration will have declined to only *one-half* in 10^{12}. Of course you can't have a half a nucleus; this just means that the concentration has been reduced to one for every $\boldsymbol{2} \times 10^{12}$ ^{12}C nuclei. If we observe a ratio of one for every $\boldsymbol{4} \times 10^{12}$ ^{12}C nuclei, that must mean that ***two*** half-lives have elapsed – 11,460 years.

Question: Suppose a fresh sample of biological material is examined that shows 200 decays per second of ^{14}C nuclei. (This is either living tissue, or something that died within the past few years.) How many decays per second would be observed if this same sample were examined 5730 years later? ***Answer:*** 100 decays per second. The number of radioactive nuclei has decreased; there are now only half as many as there were originally. The decay constant is still the same, so the ***fraction*** of the number present that decay each second is the same as before. But since the ***number present*** has decreased to half of its original value, the ***number of decays per second*** must also have decreased to 50% of ***its*** original value.