PHY140Y

34 Nuclear Decay

34.1 Overview

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34.2 Nuclear Decays and Radiation

As we mentioned earlier, there are a number of atomic nuclei that are unstable. These decay in one of three ways, each being characterized by the type of radioactive particle (or "radiation") they emit and by the rate of decay.

34.2.1 α Decay

The process of "alpha decay" is when a nucleus emits an α particle, which is a clump of two protons and two neutrons, or a prosaic helium nucleus. This form of decay is very common with heavy nuclei such as ${}^{222}_{86}\mathrm{Rn}$, which decays via the process

$$ {}^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + \alpha \tag{1} $$

into polonium, which itself subsequently decays. This isotope of radon, by the way, is the primary source of the low levels of radioactivity that are occassionally found in the basements of homes. The gas ${}^{222}_{86}\mathrm{Rn}$ is a byproduct of the decay of longer-lived isotopes, but its relatively fast decay rate ends up being a source of α particles.

Alpha particles are generally slow-moving, as they are rather massive. However, because they are charged, they interact strongly with materials. They can penetrate into materials and can cause significant damage, especially to tissue.

34.2.2 beta Decay

Beta particles are in fact electrons, so β decay somehow involves the creation of an electron. In fact, what is at work here is a new force that we haven't previously discussed – the "weak force." When a nucleus undergoes a β decay, what in fact is happening is one of the neutrons in the nucleus undergoes the decay

$$ n \rightarrow p + e^- + \bar{\nu}_e . \tag{2} $$

When this occurs inside a nucleus, the daughter proton remains in the nucleus but the electron escapes and becomes the β ray, and the electron neutrino ($\bar{\nu}_e$) that is produced slips away without interacting (almost all of the time).

When a nucleus undergoes β decay, the change in the number of neutrons and protons changes the name of the nucleus. Thus

$$^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + e^{-} + \bar{\nu}_e \tag{3}$$

effectively transmutes cobalt into nickel (and is a very common β ray source used in hospitals for radiation therapy).

The resulting β particle is really a fairly energetic electron. Since the electron is charged but very light, it interacts almost immediately with material and therefore it is not consider a strongly penetrating form of radiation (though the more energetic the electron, the deeper are its effects).

34.2.3 γ Decay

The last form of radioactive decay arises from nuclear processes that produce γ rays, or very energetic photons. These are produced primarily when a nucleus is produced in an "excited" state, similar to an excited hydrogen atom with principal quantum number $n > 1$. In order to decay to the ground state of the nucleus, it will typically emit an energetic photon, known as a gamma ray, or a γ.

The energies of gamma rays can range from what we would normally call x-rays (a few keV) up to true gamma ray energies of a few MeV or more. Energetic γ's have similar effects to β rays of the same energy. They interact in materials, and as with β rays can have harmful effects on tissue. They have clearly many beneficial usages, ranging from the traditional x-ray machines to CAT scanners.

34.2.4 Decays of Radioactive Materials

The decays of heavier isotopes are not typically simple processes, as they often include several different types of decays yielding different unstable nuclei with different lifetimes. A good example is given by the an isotope of thorium, ^{232}Th. The decay chain associated with ^{232}Th involves an α decay followed by two β decays, and is illustrated in Fig. 1. The resulting nucleus is again thorium, but with a mass number that is 4 lower.

Besides the three types of radiation discussed above, these decays often can release neutrons. Neutrons turn out to be a rather important product of nuclear reactions, and in themselves form a type of radiation that is potentially very harmful due to the fact that the neutrons can penetrate through large amounts of matter and cause significant damage.

34.3 Decay Rates, Lifetimes and Half-Lives

A typical unstable nucleus will decay in one of the ways described above, and often can decay in several different possible ways. In order to understand how to characterize these decays, let's review how we would describe the decay of a large number N of unstable nuclei.

The primary postulate is that for a sufficiently short time δt, each nucleus has a probability of decaying that is independent of the other particles in the sample. We can write the probability

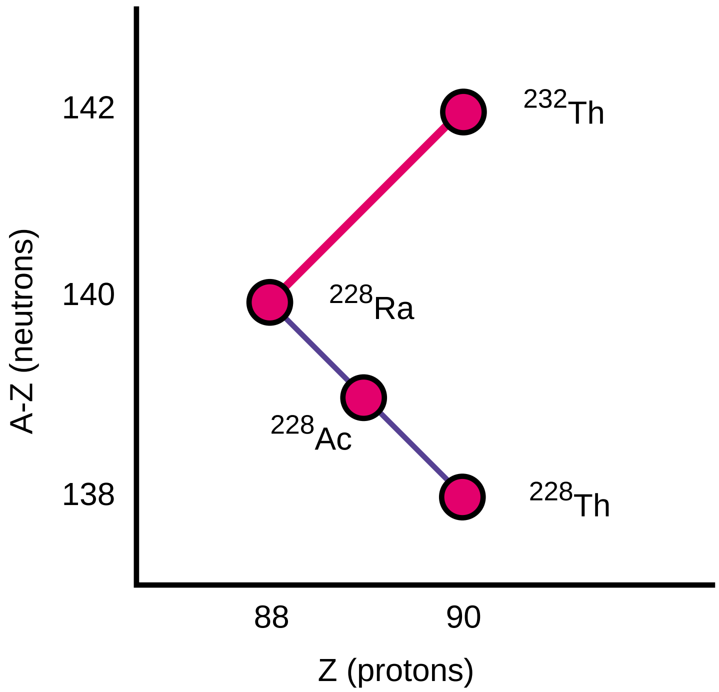

Figure 1: The initial decay chain of a thorium isotope, showing the sequence of decays that occur.

that a given nucleus will decay in this time interval as

$$P = \lambda\delta t, \tag{4}$$

where λ is a constant with units of 1/time. Then in this time interval, the reduction in the total number of nuclei, δN, will simply be the number of nuclei in the same at the time $N(t)$ times the probability of decay of each nucleus:

$$\delta N = -N(t)\lambda\delta t \tag{5}$$

$$\Rightarrow \frac{\delta N}{\delta t} = -\lambda N(t) \tag{6}$$

$$\Rightarrow \frac{dN}{dt} = -\lambda N(t). \tag{7}$$

This differential equation has the solution

$$N(t) = N_0 e^{-\lambda t}, \tag{8}$$

where N_0 is the number of nuclei at time $t = 0$. We call λ the decay constant, and it clearly characterizes the rate of decay. The larger λ is, the faster the nuclei will decay.

There are two other quantities that are often used in place of the decay constant. The first is the lifetime, τ, defined by

$$\tau \equiv \frac{1}{\lambda}. \tag{9}$$

Isotope	$t_{1/2}$
$^{222}_{86}$Rn	3.82 days
$^{238}_{92}$U	4.46×10^9 years
$^{14}_{6}$C	5.73×10^3 years

Table 1: The half-lives of a few radioactive species.

Since it has units of time, it is more directly interpreted as the time taken for the radioactive sample to decay to $1/e = 0.368$ of its original size. The second is the half-life, $t_{1/2}$, defined as the time required for the sample to decay to half its size, ie.,

$$N(t_{1/2}) = \frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} \tag{10}$$

$$\Rightarrow \ln(2) = \lambda t_{1/2} \tag{11}$$

$$\Rightarrow t_{1/2} = \frac{\ln(2)}{\lambda} = \ln(2)\tau = 0.693\,\tau. \tag{12}$$

Although you will stumble across all three quantities, you are most likely to dicsuss radioactive decays in terms of half-lives or lifetimes.

Table 1 lists the half-lives for a few radioactive species