CHAPTER 2

RADIATION THEORY

INTRODUCTION

Toward the end of the 1890's, scientists discovered that some minerals gave off mysterious and very penetrating radiation. This chapter describes that radiation, and a whole bunch of related stuff we've found out since then.

NUCLEAR FORCE

The nucleus of an atom contains neutrons and protons. Since like charges repel, you would expect that the closely packed positively charged protons would tend to move apart and be ejected from the nucleus. Yet, there is evidence that an even greater force exists in the nucleus, which binds it together. This force, which is not very well understood as yet*), is called nuclear force.

STABLE NUCLIDES

If this nuclear "binding" force is greater than the electrostatic repulsive force, the nucleus will remain intact and unchanging. It is then said to be stable. For example C-12 nuclei have been, and will continue to be, C-12 nuclei indefinitely because the nucleus is stable. This is true for most of the atoms we have studied so far. Altogether about 300 stable nuclides have been identified as occurring naturally. Their nuclei have combinations of protons and neutrons that are particularly stable.

As a rule, any particular nuclide is stable if it has a certain number of neutrons for its number of protons. For stable light nuclei the numbers of neutrons and protons are approximately equal (C-12 has 6 protons and 6 neutrons), whereas for the stable heavy nuclei there might be about 1½ times as many neutrons as protons (e.g., the stable Pb-208 isotope of lead has 82 protons and 126 neutrons).

RADIOACTIVE NUCLIDES

Over 1000 different nuclides have been identified. Most of these are "unstable" or radioactive. An unstable nucleus is one that has either too many or too few neutrons for its particular number of protons.

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*) This is what it said in my college textbooks when the author didn't understand what he was talking about. I'm merely following the custom.

These unstable nuclei suddenly hurl out subatomic particles in order to achieve a more stable neutron/proton ratio. They spontaneously change themselves into different and, in most cases, more stable nuclei.

Substances made up of unstable atoms are RADIOACTIVE. The stream of swiftly moving particles they fire out is called RADIATION.

A radioactive atom wants to lose energy to become stable. It does this by emitting radiation. Later on we will have more to say about this.

Although we often talk about unstable or radioactive atoms it must be remembered that it is the nucleus which is unstable. For this reason it is preferable to speak of radioactive nuclides, or radionuclides, rather than radioactive atoms.

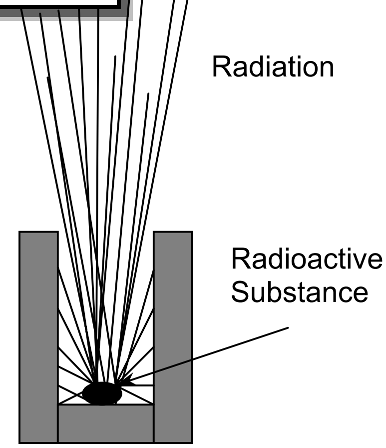


Fig. 2.1. Radiation

The process in which a radioactive nucleus emits particles is called RADIOACTIVE DECAY or RADIOACTIVE DISINTEGRATION.

TYPES OF RADIATION

Since nuclei contain neutrons and protons you might expect that in radioactive decay these particles would always be emitted. Well, you might expect that, but that's not what happens. Most radioactive atoms disintegrate by emitting alpha particles or beta particles. Atoms emitting neutrons are very rare, and proton decay is unheard of (i.e., I haven't heard of it).

An ALPHA PARTICLE is a swiftly moving particle of two neutrons and two protons. It is identical to a helium nucleus.

A BETA PARTICLE is a swiftly moving electron that has been emitted by a nucleus.

We have already learned that a beta particle is an electron that is emitted by the nucleus. How a nucleus can emit an electron when it doesn't contain any will be explained a few pages further along. Of course, whether you believe me or not is up to you.

Most of the radionuclides that emit beta particles will emit, immediately afterwards, more energy called gamma radiation or gamma rays.

GAMMA RAYS are a form of radiant energy similar to X-rays.

If certain atoms are bombarded with particles, such as alpha particles, or gamma photons, neutrons can be knocked out of nuclei to produce neutron radiation. The neutrons with high speeds (several km/s).

ALPHA RADIATION (α)

Alpha particles are emitted in the disintegration of certain radionuclides, mainly those of the heavy elements. Examples are U-235, U-238, Ra-226 and Th-230.

Why might a nuclide emit an alpha particle? The heavier a nucleus is, the more unstable it is, because the proton-proton electrostatic repulsive forces increase faster than the attractive nuclear forces. A heavy nucleus can therefore become more stable by emitting an alpha particle. This reduces the number of protons by 2 and the mass by 4 amu.

An alpha particle very soon loses its energy and slows down. At the end of its travels (a few cm in air) it grabs two orbital electrons from the free electron population around it to become an ordinary and quite undistinguished helium atom.

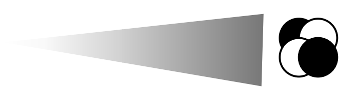


Fig. 2.2. Alpha Particle

BETA RADIATION (β)

A large number of beta-emitters are known. Most of the fission products produced in the fission process are beta emitters: in most cases their "daughters" and "grand-daughters" are also.

The fastest beta particles have a velocity that approaches the speed of light (300,000 kilometres per second). When beta particles have slowed down, which happens quite quickly, they become ordinary electrons and join the free electron population.

Fig. 2.3. Beta Particle

GAMMA RADIATION (γ)

After a nucleus has emitted a beta particle, more often than not it is still slightly unstable and will get rid of its excess energy by emitting a gamma ray immediately afterwards. The time delay between the two emissions is so short (less than a billionth of a second) that we look upon them as being simultaneous, and as being only one disintegration.

Light, radio waves, X-rays and gamma rays are all "electromagnetic" radiation (so called because they have both electric and magnetic properties). They differ from one another only in their frequencies (number of vibrations or cycles per second). Certainly visible light seems different to us than radio waves. However, this difference is due entirely to the difference in frequency; only the frequency of the radiation is important in determining its properties.

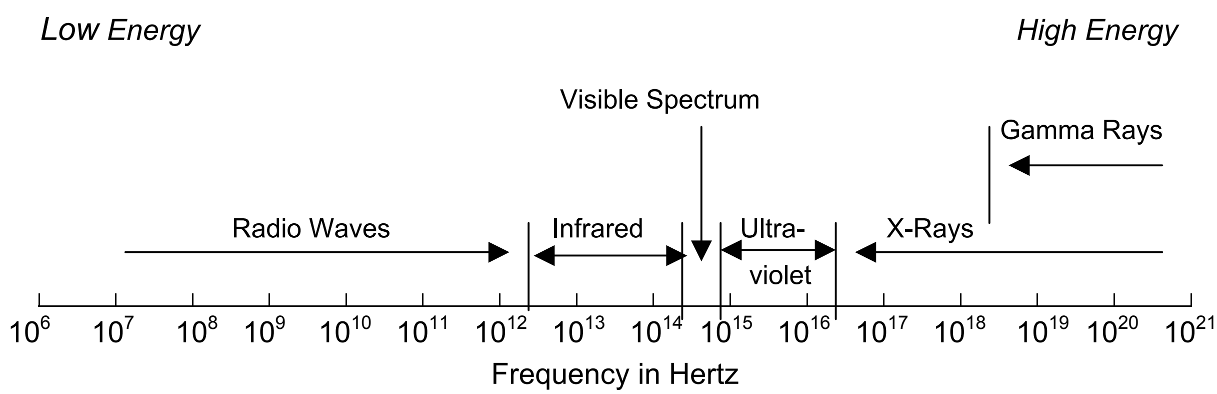


Fig. 2.4. Electromagnetic Spectrum

The energy of any electromagnetic radiation depends on its frequency. In fact, the energy and frequency are directly proportional. X and gamma rays have the highest energies. They cover about the same range of frequencies and, in fact, the only difference between them is their origin. Gamma rays are emitted from the nuclei of radioactive atoms, while X-rays are produced by disturbances in the electron orbits of atoms. X-rays are not emitted from nuclei.

In some of its properties, electromagnetic radiation is very similar to particle radiation. The radiation seems to be transmitted through space in small individual bundles of energy. Such an individual packet of energy is called a **photon**.

NEUTRON RADIATION (n)

We already know that neutrons have about the same mass as protons, but no electrical charge. The interactions of neutrons with matter are complicated, and will be discussed in detail later on. Trust me.

RADIATION AND ENERGY

The penetrating ability of any kind of radiation depends on its energy. Therefore, before we can discuss the penetrating ability of the different types of radiation we should first learn a little bit about energy.

A bullet held in your hand is quite harmless. If it is shot from a gun it has great speed, and is very damaging, especially if it hits you. Similarly, subatomic particles are harmless when they are lurking about inside atomic nuclei. Yet when they are emitted from nuclei, the particles have high speeds that depend on the amount of energy that they were given. These amounts of energy are very small compared to our usual energy units. Therefore, the energies of these particles are expressed in a special unit, called the **electron volt**, abbreviated to **eV**.

For larger energy changes, multiple units of the electron volt are used. These are:

1 thousand eV = 1 keV = 1E3 eV

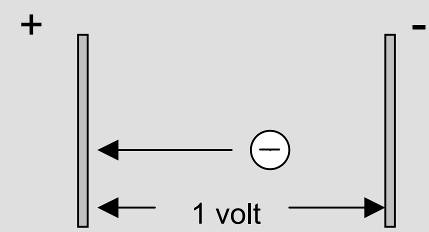
1 million eV = 1 MeV = 1E6 eV

Radiation emitted from radionuclides typically has energies ranging from a few keV to a few MeV.

Just over six million million MeV are the same as one joule of energy. (You use a joule of energy in raising a weight of 1 kg one metre.) You can see from these numbers that even an MeV is still only a very tiny amount of energy, perhaps even less than some of you are expending in trying to understand this stuff.

If you want to know more, look at the box on the right. This is more detailed information that's nice to know, but not "need to know". We'll use this approach of putting harder stuff in shaded boxes from now on.

The diagram below shows an electron in an electric field. It is attracted to and moves towards the positive electrode.



An electron volt is the amount of energy that the electron would gain in passing through this potential difference of one volt. If the charged particle were a proton, it would move to the negative electrode, but it would also gain energy of 1 eV. Although the energies they pick up are the same, the electron would travel much faster because it is so much lighter.

Even 1 MeV is still tiny in conventional terms. For example:

1 kWh = 2.25E19 MeV

1 joule = 6.24E12 MeV

IONISATION: The Formation of Ion Pairs

You've already learned that the positive charge of an atom resides in its nucleus and the negative charge is contained in orbiting electrons zipping around it. A neutral atom (i.e., one that has no net charge) therefore has as many electrons travelling in regular orbits around the nucleus as there are protons inside it. If this atom were to lose one of its electrons, it would be left with a net positive charge, and would be known as a **positive ion**. (The Greek word "ion" means traveller.)

The liberated electron is **a negative ion** and the two particles together are called an **ion pair**. These two ions move about quite independently of one another.

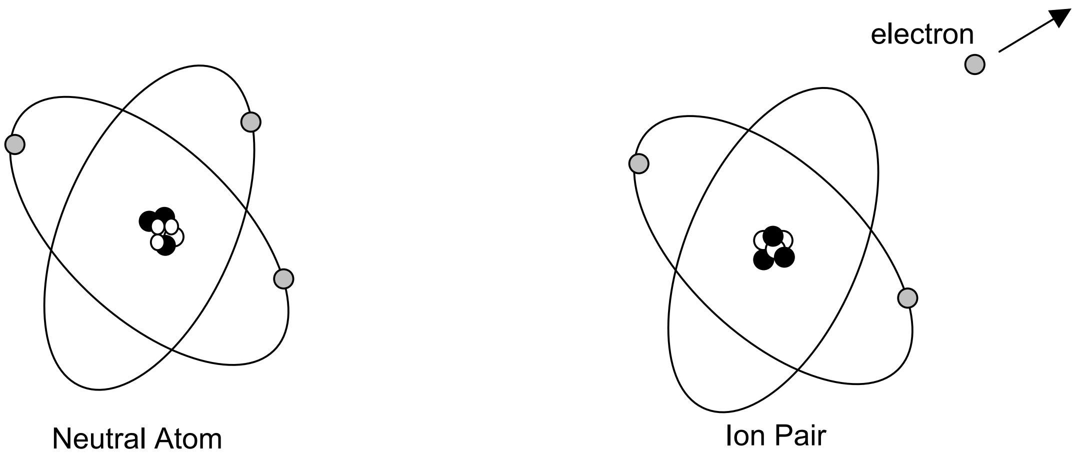


Fig. 2.5. Ionisation

The process that produces ion pairs is called IONISATION.

IONISATION BY ALPHA AND BETA PARTICLES

A swiftly moving charged particle creates a strong electric field in its immediate neighbourhood. This "field" is similar in nature to the more familiar field of a magnet, and it has the ability to remove orbital electrons from atoms. In this way alpha and beta particles cause the formation of a lot of ion pairs in their paths. (This is not quite so for gamma radiation — we shall deal with gamma ionisation separately a bit later).

Because alpha particles are over 7000 times more massive than beta particles, they will move much more slowly than beta particles of the same energy. Also, they won't be deflected from their path, unlike beta particles. A slow moving particle spends more time near the atoms or molecules among which it is passing, and therefore is able to produce more ions per unit distance travelled. So, the slower moving doubly charged alpha particles create more ions per millimetre of travel than do the swifter, singly charged beta particles. Alpha particles produce about 5000 ion pairs per mm of travel in air, while beta particles produce about 10 ion pairs per mm in air. (See Fig. 2.6.)

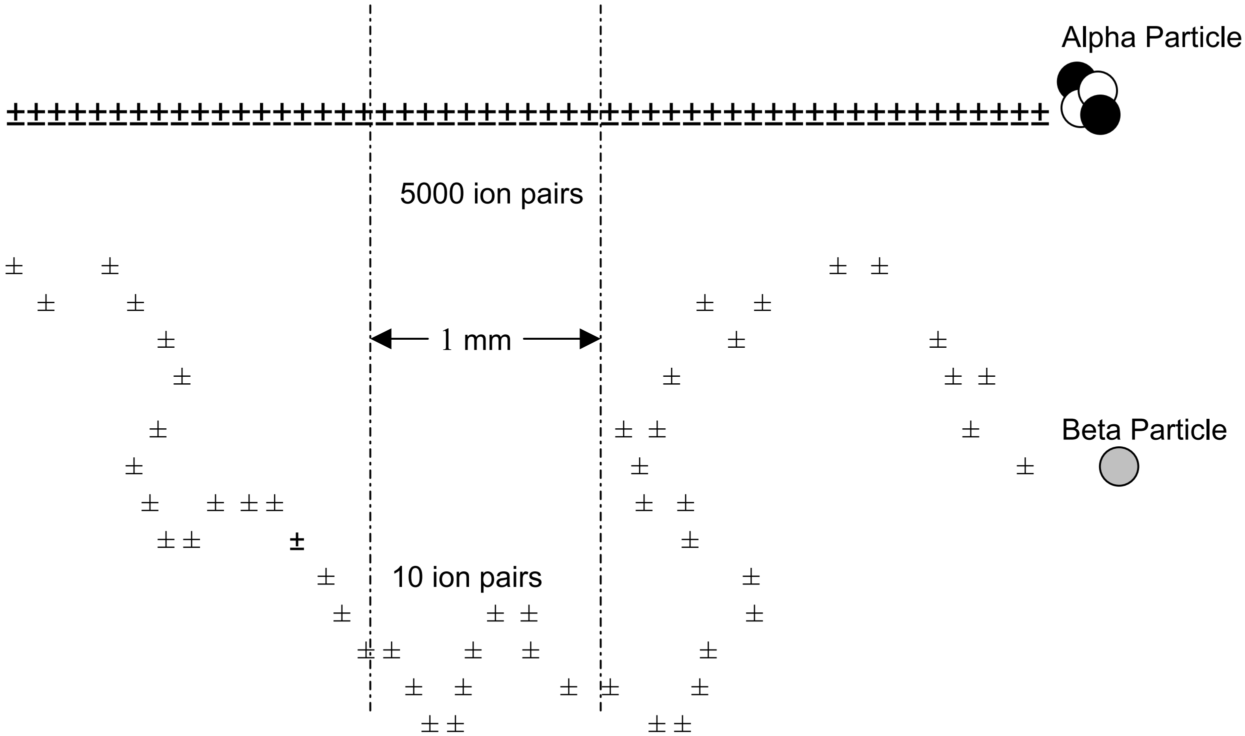


Fig. 2.6. Ionisation in Air

Alpha and beta particles of the same energy produce about the same total number of ion pairs, since the amount of energy required to produce an ion pair is the same (around 34 eV in air). However, since alpha particles produce many more ion pairs per mm than beta particles do, they lose all their energy in a relatively short distance. It is because of this that alpha sources inside the body present a much more serious radiation hazard than beta sources inside the body, i.e., the alpha particles produce a very large number of ion pairs in a small volume of tissue. And that concentration of ionisation is not good.

IONISATION BY GAMMA RADIATION

Uncharged particles have no electric field associated with them, and cannot strip electrons from atoms the way alpha and beta particles do. Gamma photons (think of the photons as packets of energy) produce ionisation indirectly as a result of collisions. Much like balls on a pool table, they either knock another ball hard enough to transfer a lot of energy to it, or they miss it entirely. This analogy is a bit simple-minded; let’s see what happens in more detail.

There are three ways in which a gamma photon can interact with an atom. Let’s look at each of these in turn.

Photoelectric Effect

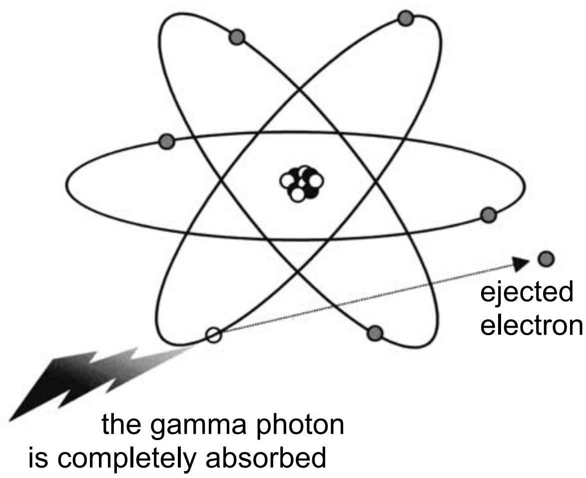


Fig. 2.7. Photoelectric Effect

If a gamma photon gets close to an electron of an atom, it can eject it from the atom. The electron takes up all the energy of the photon, and the photon disappears. This is called the **photoelectric effect**.

The speeding electron ejected from the atom will then cause ionisation in exactly the same way as a beta particle until its extra energy is completely dissipated. For this reason, we say that gamma photons produce indirect ionisation. That is, only the first electron ejected from the atom was produced directly — all the remaining ion pairs are produced indirectly by that electron.

The photoelectric effect occurs only at low gamma energies.

Compton Scattering

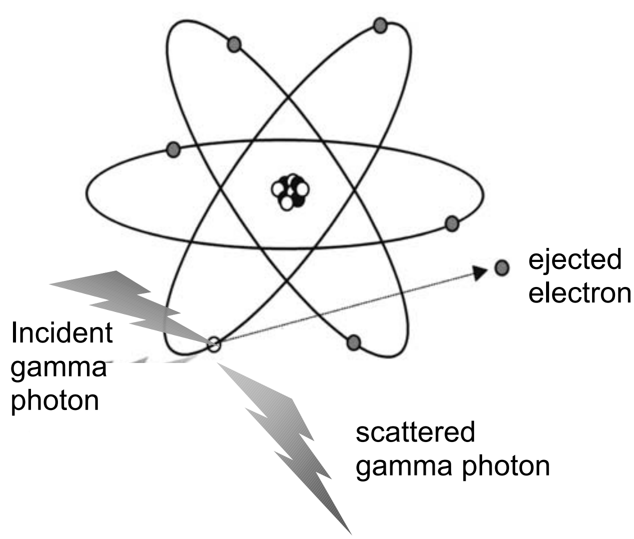


Fig. 2.8. Compton Effect

If the gamma photon energy is not low enough for this, **Compton scattering** is more likely. (It derives its name from the scientist who discovered it.) Here, the photon will transfer only part of its energy to an electron. The remaining energy is taken away by a new gamma photon of lower energy. We say that this new photon is *scattered*, because it will take off in a new direction. The electron that was ejected from the atom produces ionisation in just the same way as a beta particle.

The end result is that ionisation and a lower energy gamma photon is produced from a higher energy photon.

Pair Production

This gamma photon interaction occurs only at high gamma energies, and is rarely of importance to us in a nuclear power plant. You can find more details on all three gamma interactions in the box on the next page.

Photoelectric Effect

The chances of the photoelectric effect occurring in any material depend on Z^5, and on the photon energy. It occurs mainly with photons below 0.5 MeV, the lower the energy, the more likely it is.

Compton Scattering

The likelihood of Compton scattering depends on Z, and is predominant with photons of medium energy (from about 0.5 to 3 MeV). The scattered photon may be absorbed by the photoelectric effect in another atom, or there may be successive Compton effects until the last scattered photon has a low enough energy to be absorbed somewhere in the photoelectric effect.

Pair Production

A high-energy gamma photon sometimes changes into two electrons, one positive and the other negative. The positive electron is called the **positron**. This interaction is known as **pair production**, for obvious reasons.

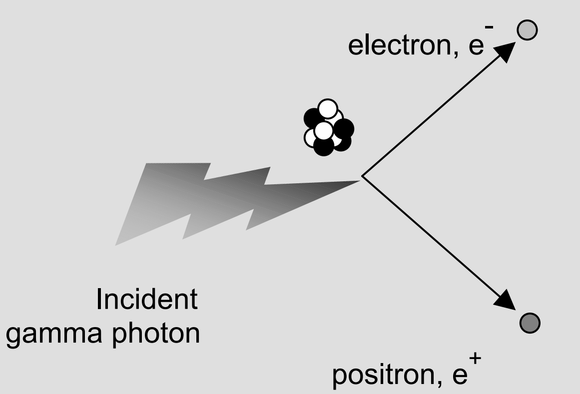


Fig. 2.9. Pair Production

This is a good example of the conversion of energy to mass. Pair production occurs only near the nucleus of an atom. The amount of energy necessary to provide the mass of the electron and positron pair is 1.02 MeV. Pair production therefore cannot happen with gamma photons with less than this energy.

The higher the photon energy, the more likely pair production is to occur. The likelihood varies roughly as $(E - 1.02)^2Z^2$.

The electron and the positron share the excess of energy (over 1.02 MeV) equally. These high-speed charged particles then cause ionisation in just the same way as the electrons produced in photoelectric and Compton scattering effects.

However, this is not the whole story. The positron slows down by causing ionisation just as the electron does, but instead of simply coming to rest, it ends up being captured by an electron. The pair then "commits suicide" to become two new photons, in a process called **annihilation**. The photons have energy of 0.51 MeV each.

This is the opposite to pair production: now mass is converted into energy. This radiation is called **annihilation radiation**. It will be scattered by the Compton effect or absorbed by the photoelectric effect in an identical manner to other gamma photons of similar energy.

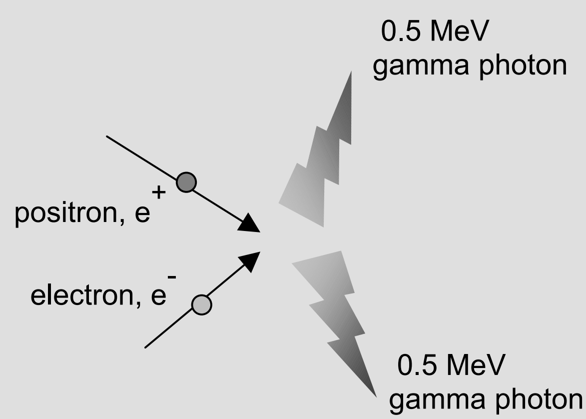


Fig. 2.10. Annihilation Radiation

Note that the photoelectric effect is the only one in which the gamma photons are absorbed completely (even in pair production two 0.51 MeV photons will still be produced at the end).

What You Should Understand About Gamma Absorption

Gamma photons interact with the electrons of an atom, so the more electrons an atom has, the greater is the chance of a gamma photon doing something. The number of electrons in an atom is equal to the atomic number Z. This means that high Z materials are much better at absorbing gamma photons than low Z materials. Lead with Z = 82 is an example of a very effective gamma absorber.

Nevertheless, the chances of a gamma photon interacting with the electrons of an atom are much less than those of a beta particle. As a result, gamma photons will travel very much further than beta particles before being absorbed. This is true for any material.

From our point of view, the main difference between the photoelectric effect and the Compton effect is that in the photoelectric effect the gamma photon is completely absorbed, but in the Compton effect it survives, although at a lower energy. This surviving gamma photon will continue to travel through the absorbing material. It may even undergo further Compton effects until it is eventually absorbed in a photoelectric effect. This is a chance event and explains why one cannot predict how far a gamma photon will travel before it is absorbed.

We say that gamma photons cause ionisation indirectly, because they transfer their energy to electrons that they knock out of atoms. It is these electrons that produce the ionisation. But regardless of how gamma photons interact with matter, the end result will be the production of electrons and positive ions. This can happen in any material, including your body, and damage to cells and tissue can occur. When you are exposed to gamma radiation, Compton and photo-electric effects will occur in all parts of your body. This means that they will produce ionising electrons fairly uniformly throughout your body, and all tissues will be exposed to harm.

IONISATION BY NEUTRONS

Neutrons have no charge and do not interact with electrons. Instead, they lose energy by reacting with nuclei rather than electrons. You will recall that neutrons have about the same mass as hydrogen atoms, so they can transfer a lot of energy to hydrogen nuclei if a direct hit is made. Just like balls on a pool table: a head-on collision transfers almost all of the energy of the cue ball to the ball being struck. So hydrogen nuclei will take off at high speed when neutrons strike them. Since the hydrogen nuclei are nothing but protons, they will produce dense ionisation in much the same way as alpha particles do.

The body contains a lot of hydrogen (about 60% of you is water) and this explains why living tissue gets badly punished by neutrons. Once the neutrons have lost most of their energy they are invariably absorbed by some nucleus. The various reactions of neutron absorption will be left for later.

THE PENETRATING ABILITIES OF α, β, γ, n RADIATION

A radiation source is any object that emits radiation. Often, sources are prepared especially for definite purposes, such as for checking the proper operation of instruments. With four suitable sources, we can set up an experiment to test the penetrating ability of the four kinds of radiation, α, β, γ, and n.

These four types of radiation have different properties, one main difference being that they will penetrate matter to different depths. This is important for deciding how to protect us against radiation.

Four radiation detecting instruments are placed opposite the alpha, beta, gamma and neutron sources. If a sheet of paper is placed between the sources and detectors, the alpha particles are stopped, but the beta particles,
neutrons and gamma rays pass through it without being diminished.

If a sheet of aluminum about 5 mm thick is used as an absorber, both alpha and beta particles are totally absorbed, but the neutrons and gamma rays are reduced only very slightly. A 10-mm sheet of lead is required to reduce the intensity of the gamma rays and neutrons significantly.

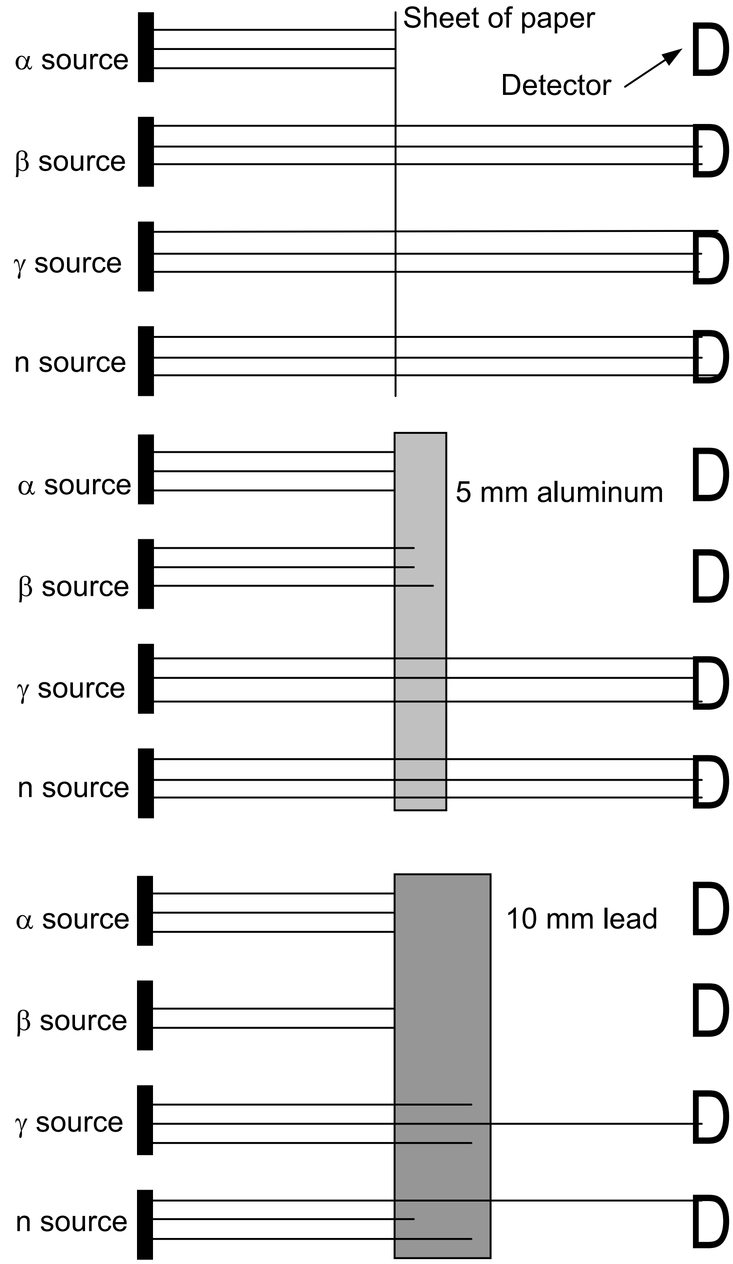


Fig. 2.11. The Penetrating Power of Radiation

Although alpha particles are unable to penetrate a few sheets of paper or a thin aluminum foil, they do travel through several centimetres of air, knocking off electrons from perhaps 200,000 atoms of nitrogen and oxygen before the excess energy is spent. You can see that different materials permit the passage of alpha particles to different extents.

The alpha particles emitted from any one type of radionuclide all have a constant energy. For example, the alpha particles emitted by U-238 all have an energy of 4.18 MeV, and those emitted by Ra-220 all have an energy of 7.46 MeV.

The range of energies from different types of alpha-emitting radionuclides is from 4 MeV to 8 MeV. The graph at the right gives the range of alpha particles in air for different energies.

These energies are not sufficient to enable alpha particles to penetrate even the protective, dead, outer layers of the skin.

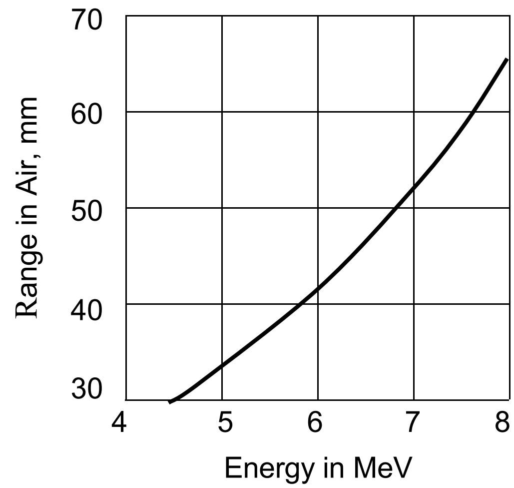


Fig. 2.12. Range of Alpha Particles in Air

Because of this, alpha sources that are outside the body **do not present an external radiation hazard**. However, when alpha sources are taken into the body they become a **serious internal radiation hazard** for reasons that we will discuss later.

BETA RADIATION

Many radionuclides produced in a nuclear reactor are beta emitters. You will remember that beta particles are high-speed electrons fired out of the disintegrating nucleus.

Beta particles are much more penetrating than alpha particles. Beta particles will penetrate about a centimetre of tissue, and if the source is sufficiently strong, they will cause a burn to the skin. Therefore, beta radiation is an external radiation hazard, but one that is not difficult to deal with, since a sheet of plywood is enough to stop them. If the beta source should find its way into the body, the hazard is greatly increased, although such sources are still less harmful than alpha sources inside the body.

Early work in nuclear physics showed the beta particles emitted by any given beta emitter had a range of energies. This is quite unlike other known radiation, such as alpha and gamma, which are always emitted with the same energy from the same radionuclides.

For example, the beta particles emitted by Sr-90 can have energies all the way from zero up to a definite maximum level, $\mathbf{E_{max}}$**.** Figure 2.13 shows the beta energy spectrum of Sr-90. In other words, it is a graph of the relative numbers of beta particles at various energies.

You'll see there that the maximum energy of the beta particles emitted by Sr-90 is 0.54 MeV. A few of the particles will have nearly this energy level, but most will have lower levels, and some will be very low. The average energy of the beta particles is about one third of the maximum energy, E_{max}.

It is the maximum energy of the beta particles which is characteristic of the nuclide, and it is this which is given in reference tables.

The maximum energy of beta radiation from most beta emitters lies between 0.1 and 3 MeV, but some are found above and below these values. Fig. 2.14 shows the penetrating ability of beta radiation in air.

Note that the scales on this graph look odd. It is a logarithmic graph where each decade rather than each unit has an equal width. This lets us capture a large range of values on one graph. We'll be using this type of graph quite a bit.

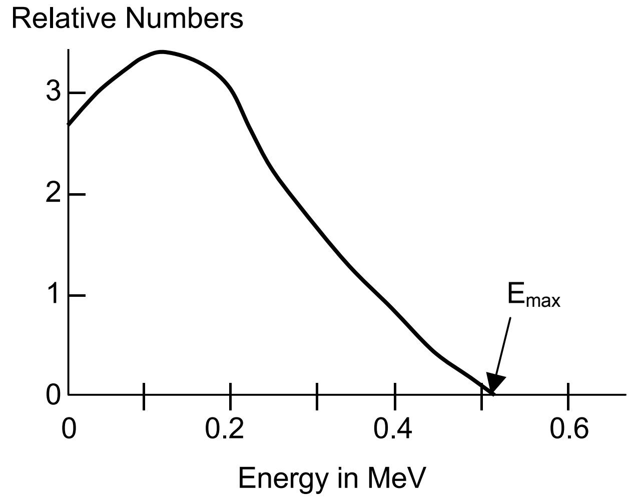


Fig. 2.13. Beta Energy Spectrum of Sr-90

Heavy dense materials are most effective in stopping beta particles. Unfortunately high-energy beta particles produce X-rays when absorbed. This effect is much more severe with absorber materials of high atomic numbers (lead, etc.) than of low atomic numbers (glass, Lucite, wood, etc.). These X-rays (called **Bremsstrahlung** from the German: braking radiation) are more penetrating than the original beta particles.

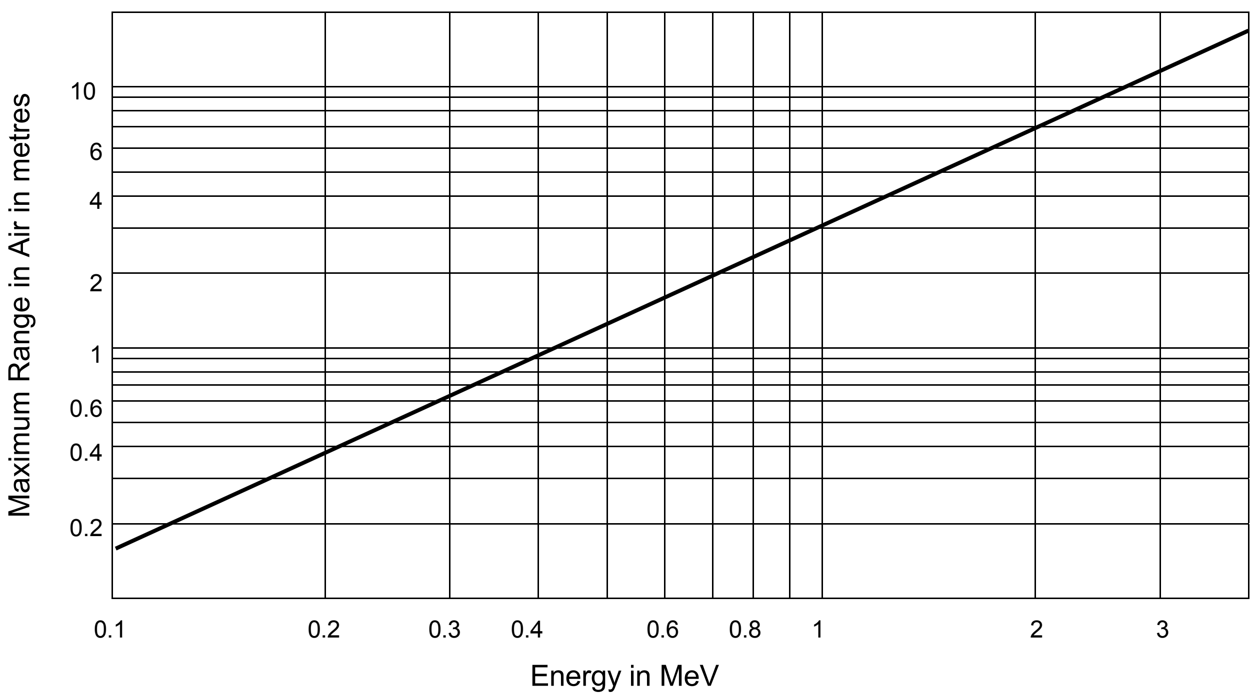


Fig. 2.14. Range of Beta Radiation in Air

Fig. 2.15 shows that heavier materials are better than lighter materials for shielding against beta radiation. As heavier materials can also produce X-rays, shielding against this radiation must also be allowed for by increasing the shielding thickness. In practice, we often use lead blankets for shielding against beta fields: lead is useful for shielding the gamma radiation that is usually found with beta radiation. On those rare occasions when the beta fields are much stronger than the gamma fields, it may be best to use plywood or neoprene rubber sheeting.

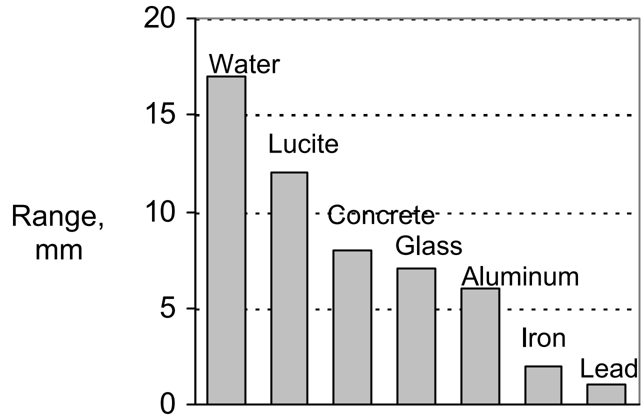


Fig. 2.15. Maximum Range of 3MeV Beta Particles in Various Materials

GAMMA RADIATION

Gamma radiation can penetrate to great depths in materials. In theory, you won't stop all of the gamma radiation, regardless of how much shielding you use. So what you usually do in practice is to use enough absorbing material so that the radiation is reduced to an acceptable level. Since there isn't anything that stops gamma completely, a useful quantity for comparing absorbers is the **half-value layer (HVL)**.

> **A HALF-VALUE LAYER is the thickness of material that reduces the gamma radiation intensity by one half.**

Most gamma photons have energies below 3 MeV, although there are some exceptions. The higher the gamma energy, the greater its penetrating ability. This is illustrated in Fig. 2.16; it shows the half-value layer of water required for various gamma energies.

You would need about 100 mm of water to reduce the level of 1 MeV gamma radiation by half, whereas about 150 mm of water would be required for the same reduction with 2 MeV gamma radiation.

Water is OK as an absorber for gamma radiation, but there are better ones. The most effective materials for absorbing gamma rays are those that contain a lot of orbital electrons for the gamma photons to interact with. These are elements with a high atomic number (i.e., lots of electrons per atom) and a high density (i.e., lots of atoms per unit volume). This is why lead is such a good gamma shielding material.

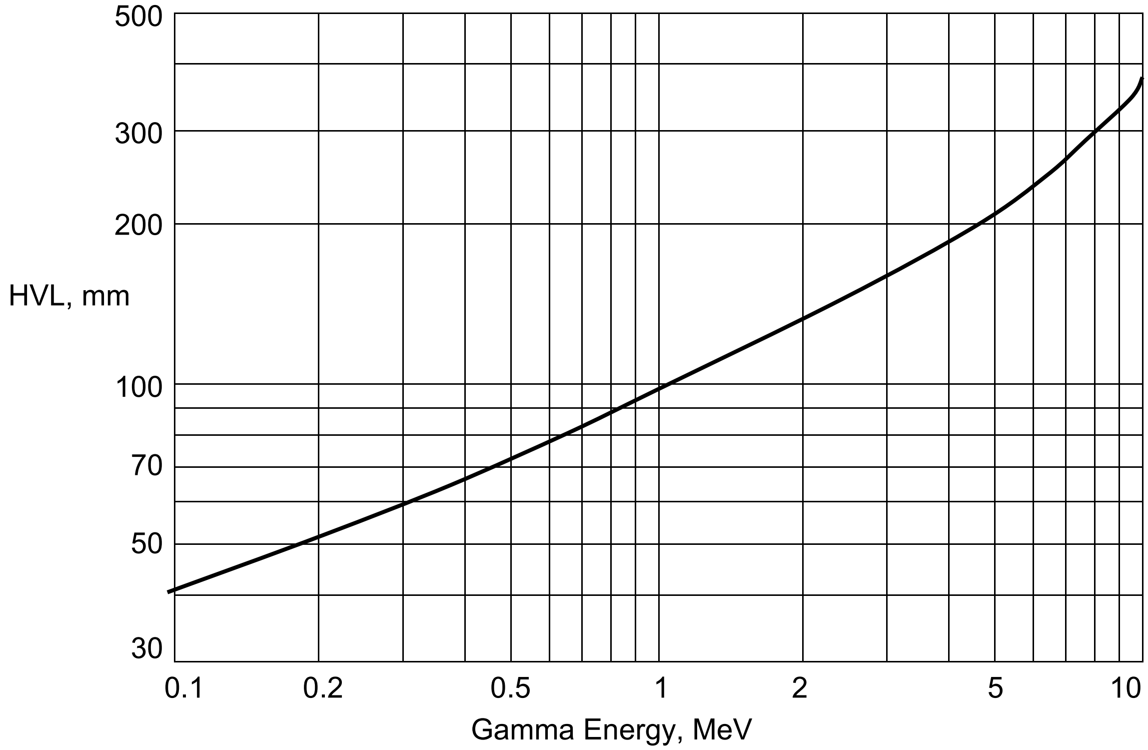


Fig. 2.16. Half-Value Layer of Water for Various Energies

You can see from Fig. 2.17, that 15 mm of lead is equivalent to about 80 mm of aluminum as an absorber for 3 MeV gamma radiation. Because of its low density, air isn't much use: the HVL is about 220 m for 3 MeV gamma radiation.

Another interesting comparison is the range of beta radiation and the half-value layer for gamma radiation. 17 mm of water will completely absorb 3 MeV beta radiation (see Fig. 2.15), but you need about ten times that much to reduce 3 MeV gamma radiation to half.

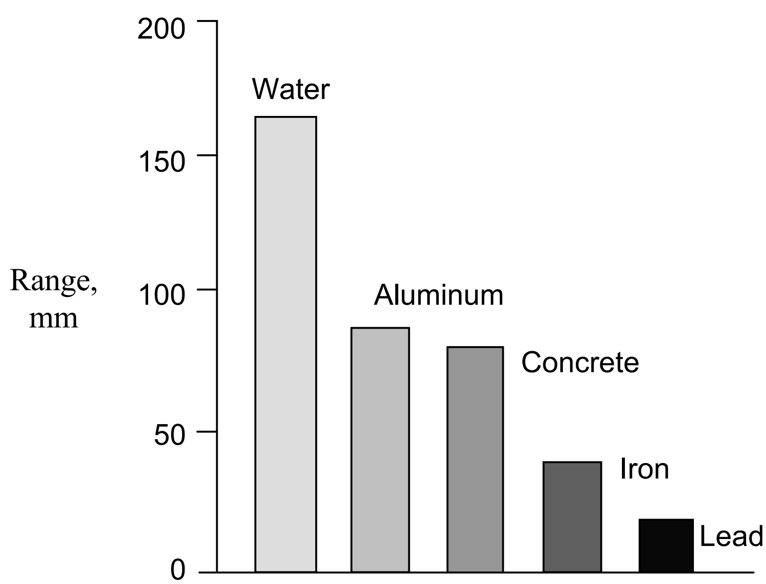


Fig. 2.17. HVLs for 3 MeV Gamma Radiation

The HVL concept is used only for gamma radiation, because alpha and beta radiation will be completely absorbed after a certain distance, whereas gammas won't.

NEUTRON RADIATION

The way in which neutrons interact with matter depends to a large extent on their energies, which can range from several MeV down to fractions of an eV. We are going to treat neutron radiation in detail later on. For the time being it is sufficient to say that neutron ranges are fairly similar to gamma ranges. The main difference is due to neutrons being particles: they must be slowed down before they can be absorbed. (The chances of them being absorbed while they still have high energies are negligible.) Water is an excellent material for slowing them down because they make many collisions with the light hydrogen nuclei (i.e., protons). Once they are slowed down, it is fairly easy to absorb them; for example, slow neutrons will be reduced by a factor of 10 when travelling through 100 mm of water or tissue.

DECAY SCHEMES

When radioactive atoms decay (disintegrate), their nuclei emit particles. Any nucleus that emits alpha or beta particles changes its atomic number. Therefore, it becomes a totally different nucleus. The decay process and the new nucleus produced by the decay are discussed in this section.

ALPHA DECAY

Many of the heavy radionuclides (either naturally occurring or artificially produced) are alpha emitters. As mentioned before, alpha particles (α) consist of two neutrons and two protons, and are identical to helium nuclei (He-4).

Any nucleus that has lost two neutrons and two protons has to be a nucleus of another element. U-238, which is an alpha emitter, has an atomic number of Z = 92 (number of protons). When a uranium atom loses two protons, its atomic number becomes 90.

That's thorium (Th, see page 5). For example, U-238 has a mass of 238, which following the loss of the four mass units of the alpha particle becomes mass 234. Therefore, the new nucleus formed by the alpha decay of U-238 is Th-234. You show alpha decay in either of these ways:

$$_{92}U^{238} \longrightarrow {}_{90}Th^{234} + \alpha$$

$$_{92}U^{238} \longrightarrow {}_{90}Th^{234} + {}_{2}He^{4}$$

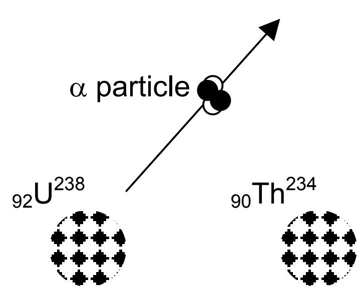


Fig. 2.18. Alpha Decay

In the decay process, the disintegrating nuclide (U-238 in our example) is called the **parent.** The nuclide resulting from the decay (Th-234 in the example) is called the **daughter**. There are no sons. No point complaining to the Human Rights Mob: nuclides aren't people. To determine which daughter nuclide is formed in an alpha decay, simply subtract two from the atomic number, Z, and four from the mass number, A, of the parent nuclide.

Three more examples of alpha decay:

(1) Uranium-235 to thorium-231: ${}_{92}U^{235} \longrightarrow {}_{90}Th^{231} + {}_{2}He^{4}$

(2) Thorium-232 to radium-228: ${}_{90}Th^{232} \longrightarrow {}_{88}Ra^{228} + {}_{2}He^{4}$

(3) Radium-226 to radium-222: ${}_{88}Ra^{226} \longrightarrow {}_{86}Rn^{222} + {}_{2}He^{4}$

BETA DECAY

Almost all radionuclides produced in reactors and some naturally occurring radionuclides are beta emitters.

In beta decay, the nucleus ejects an electron. Since the nucleus does not contain electrons, you now finally get to find out what gives. A review of Table 2.1 may help you to understand this process. Then again, it may not.

In beta decay a neutron changes into a proton and an electron (beta particle). The loss of an electron of negligible mass hardly alters the mass of the neutron, and it remains at 1 amu, which is equal to the mass of the proton. When the neutron loses an electron (i.e., a negative charge), the new particle is left with a single positive charge, which is the same as the charge on the proton.

So, the neutron turns into a proton. The proton remains in the nucleus and the electron is fired out. This electron is the beta particle.

TABLE 2.1. SUBATOMIC PARTICLES

Particle	*Symbol*	*Mass (amu)*	*Electrical Charge*
Proton	p	1	+ 1
Neutron	n	1	0
Electron	e	1/1840	– 1

The daughter nucleus now contains one less neutron and one more proton than the parent nucleus. Therefore, the atomic number Z (number of protons) increases by one, and the number of neutrons decreases by one. The mass number A, which is the sum of the number of neutrons and protons, remains unchanged. Although the atom now has Z + 1 protons, it still has the original number of Z electrons, and therefore a net charge of +1. To become electrically neutral, it grabs an electron from the mob of free electrons around it.

As an example, the beta decay of tritium (H-3) is illustrated below:

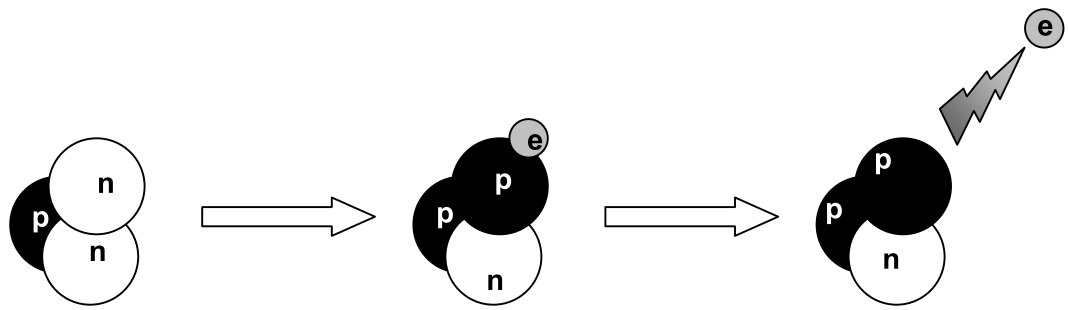


Fig. 2.19. Beta Decay of Tritium

Some other examples of beta decay are given below:

(1) Potassium-40 (K-40 decays by β^- to calcium-40 (Ca-40): $_{19}K^{40} \longrightarrow {}_{20}Ca^{40} + \beta^-$

(2) Lead-214 to bismuth-214: $_{82}Pb^{214} \longrightarrow {}_{83}Bi^{214} + \beta^-$

(3) Protactinium-234 to uranium-234: $_{91}Pa^{234} \longrightarrow {}_{92}U^{234} + \beta^-$

POSITRON EMISSION

We came across the positron earlier in this chapter in the detailed discussion of pair production. The positron is a particle exactly equal in mass to the electron, but it has an opposite (positive) charge. Some radionuclides decay by positron emission.

This type of decay is very rare with the types of radionuclides we deal with in the nuclear power industry. You are more likely to come across this in nuclear medicine. I only mention it here for the sake of completeness.

As you might expect, positron emission is opposite to β^- decay; a proton changes to a neutron by the emission of a β^+:

$$_{6}C^{11} \longrightarrow {}_{5}B^{11} + \beta^+$$

Positron emission always leads to annihilation radiation. When the positron has slowed down by producing ionisation, it combines with an electron to give two 0.511 MeV photons. This is exactly the same process as was described for pair production before.

Positron Emission Tomography is an imaging technique used in medicine. A compound labelled with a short-lived positron emitter like Carbon-11 is injected into the body. The positrons from the C-11 produce gamma photons that are detected outside the patient. The data from the detectors are analysed by computer to produce images of the organs being scanned.

GAMMA DECAY

When a daughter nucleus is formed by radioactive decay, some energy is carried away from the nucleus by the particle emitted. After most disintegrations, however, the daughter still possesses more energy than is normal for that nucleus, and we say that the nucleus is in an **excited state**. Any nucleus in an excited state promptly gets rid of the excess energy by emitting a gamma photon. Since there is no change in mass or electrical charge, gamma emission does not change the structure of the nucleus as do alpha or beta emissions. The excited nucleus is the same nucleus as the normal or **ground state** nucleus, except that the excited nucleus has more energy. The excited state is indicated with an asterisk (*) like this: Ni-60*.

Gold-198 (Au-198) decays by beta emission to an excited state of mercury-198 (Hg-198*). An asterisk is used to indicate an excited state. The decay scheme for gold-198 is as shown at the right.

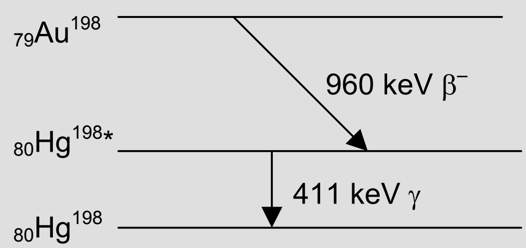


Fig. 2.20. Decay Scheme of Gold-198

This example of beta-gamma decay, where one gamma photon is emitted for each beta disintegration, is the simplest type. A more complicated (but also more common) example is the beta decay of cobalt-60 (Co-60) to an excited state of nickel-60 (Ni-60*) which then immediately emits two gamma photons in succession (see Fig. 2.21).

After the beta emission, the excited state of Ni-60 decays by gamma emission (1.17 MeV) to a lower excited state of Ni-60, which in turn decays by gamma emission (1.33 MeV) to the ground state of Ni-60.

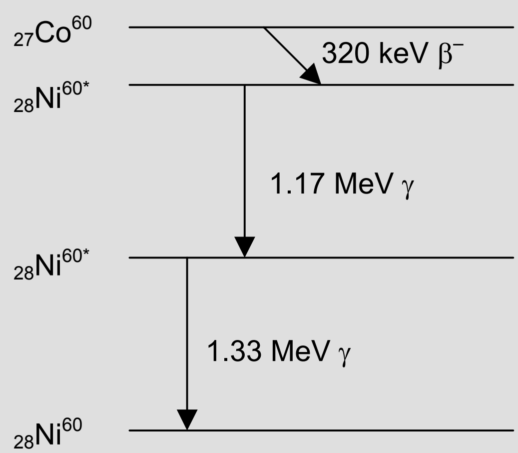


Fig. 2.21. Decay Scheme of Cobalt-60

The beta energies shown in Figs. 2.20 and 2.21 are the maximum beta energies. Since the average beta energy is only about one third of the maximum, you may wonder what happened to the other two thirds.

Believe it or not, this energy is carried off by a weird particle called the neutrino. The easiest thing to understand is its name: it comes from the Italian and means "little neutron". The neutrino has no charge, no mass, doesn't interact with anything for all practical purposes, but has energy, spin and momentum. You're welcome.

Some radionuclides have very complicated decay schemes where the beta emission is followed by a series of gamma emissions. In spite of the fact that both a beta particle and gamma rays are emitted, such disintegrations or decays are still considered to be a single event because the emissions occur virtually simultaneously. (For those of you who must know, the time delay between the beta and gamma emissions is less than the time it takes light to travel one mm, OK?) Most radionuclides produced in a nuclear reactor emit both beta and gamma radiation.

DECAY SERIES

When radionuclides decay, the daughters can be stable nuclides, or they can be radioactive. Calcium-40, the daughter of potassium-40, is a stable isotope of calcium. Nickel-60, the daughter of cobalt-60, is also a stable nuclide.

However, many daughter products are themselves radioactive. Let's use strontium-90 (Sr-90) as an example. Sr-90 decays by beta emission to yttrium-90 (Y-90), a radioactive nuclide. The Y-90 then decays to zirconium-90 (Zr-90), a stable nuclide:

$$ {}_{38}\mathrm{Sr}^{90} \xrightarrow{\beta^-} {}_{39}\mathrm{Y}^{90} \xrightarrow{\beta^-} {}_{40}\mathrm{Zr}^{90} $$

Some decay series are quite long. The naturally occurring heavy radionuclides can be divided into three rather lengthy disintegration series called the uranium series, the thorium series, and the actinium series.

The uranium series starting with U-238 is shown opposite in Fig. 2.22. The end product is stable lead-206. The atomic number Z is plotted versus the neutron number N. The mass number of a nucleus in any particular square is the sum of the number of neutrons and protons ($A = N + Z$) corresponding to that square. I've filled in the first few squares for you; I'd like you to complete the rest so that you'll have some practice in identifying the daughters of α and β^- decay.

In beta decay one neutron changes to a proton, so the arrow points to a square which has one less neutron and one more proton.

In alpha decay, two protons and two neutrons are lost, so the arrow points to a square which has two protons less and two neutrons less.

Just to prove that you're up to speed, complete the table at the right.

Decay	Parent	Daughter
α	Z, A	Z – 2, A – 4
β	Z, A	
γ	Z, A	

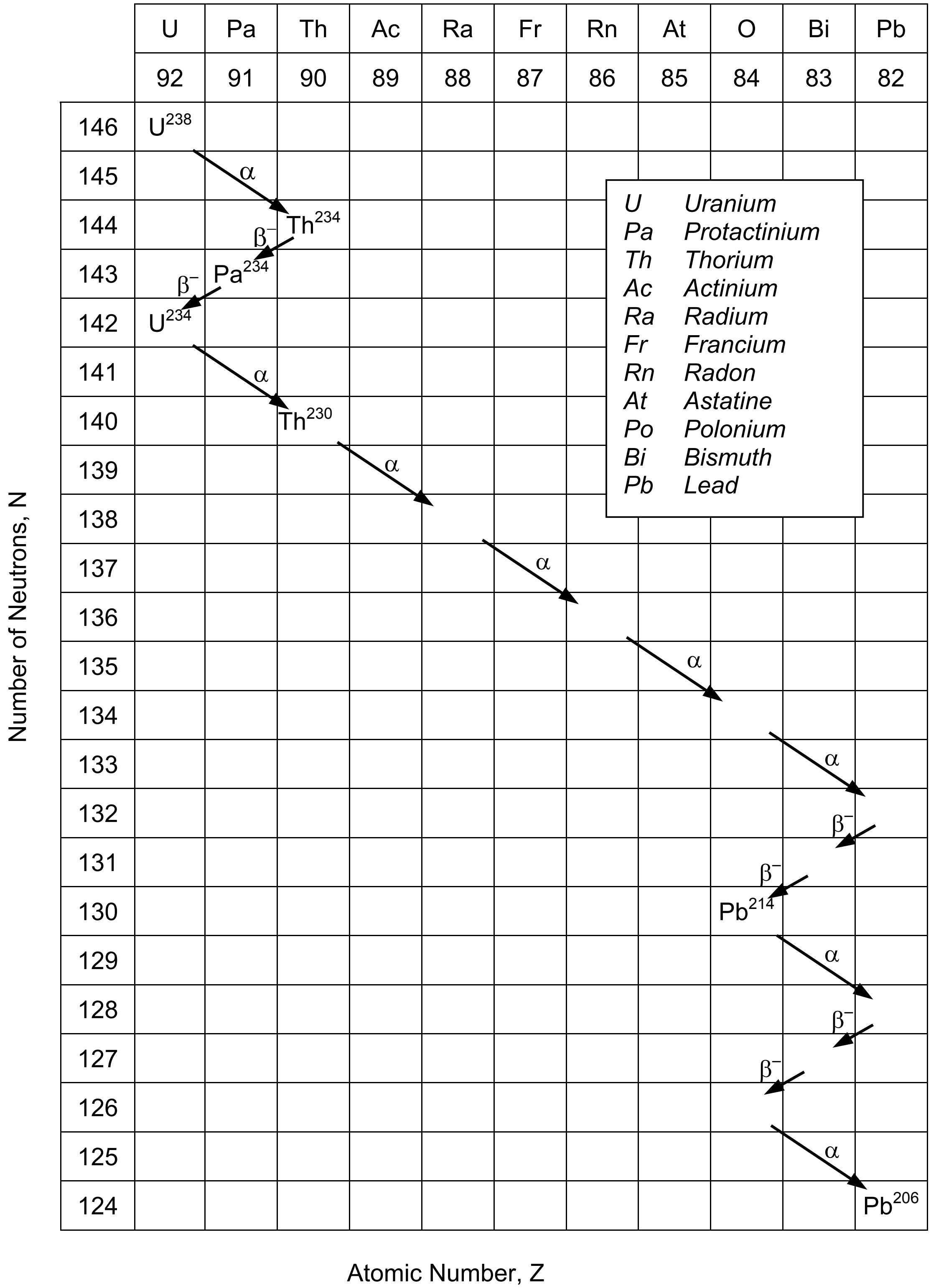


Fig. 2.22. The Uranium Decay Series

HALF-LIFE

Quite early in the history of radioactivity, it was realised that a radioactive substance loses its radioactivity with time. We will now discuss the rate at which this happens.

Let's suppose that you have a source containing a certain radioactive substance, and that its decay rate is such that 10% of the total number of atoms left decay every second. Let's also suppose that the source contains 100 million radioactive atoms, all of one kind. During the first second, 10% of them will decay. The number of disintegrations per second is therefore 10 million. This is known as the **activity** of the source, i.e.,

The ACTIVITY of a radioactive source is the number of atoms decaying per second.

Now let's get back to our example. At the end of the first second, 10 million atoms have decayed, so 90 million will be left. Of these, 10% or 9 million, will decay in the next second to leave 81 million. In the third second, 10% of these will decay, and so on. In this way, the activity of the source will decrease every second.

After a certain time it will have only half of the original activity. This period of time is called the **half-life** of the source.

Time, Seconds	No. of Atoms Left	Activity
0	100 M	10.0 M
1	90 M	9.0 M
2	81 M	8.1 M
3		
4		
5		
6		
7		
8		

The HALF-LIFE of a radionuclide is the time it takes to lose 50% of its activity by radioactive decay.

I'd like you to fill out the rest of the table to work out the half-life of our source. The method is simple: after every second, remove 10% of the atoms that remain, until only half of the original number of atoms are left. The time required for this is the half-life. If I did it right, your half-life should turn out to be about 7 seconds.

Each radionuclide has its own particular half-life that never changes, regardless of the quantity or form of the material (i.e., solid, liquid, gas, element or compound) or its past history. Half-lives range from microseconds for some radionuclides to millions of years for others. Some examples are given in Table 2.2.

After only 7.1 seconds, half of the atoms of N-16 will have decayed, and because only half of the N-16 atoms remain then, at that time the number decaying each second will also be only half the original value. On the other hand, 4.5 billion years must pass before half of the atoms in a sample of U-238 disintegrate.

Just think: if the half-life of U-235 were only 7 million years instead of 700 million, there wouldn't be any left now, and we'd all have to work in a filthy, noisy coal-fired plant instead of a nice clean nuclear plant.

Since each radionuclide has its own particular half-life, determining the half-life often helps to identify

TABLE 2.2. SOME HALF-LIVES

Radionuclide	*Half-Life*
Nitrogen-16	7.1 seconds
Argon-41	1.8 hours
Iron-59	45 days
Hydrogen-3	12.3 years
Radium-226	1600 years
Uranium-235	7E8 years
Uranium-238	4.5E9 years

The first half-life period reduces the activity to ½ of the original activity. In the second half-life the activity is reduced to ½ of the remaining activity, that is ½ of ½ = ¼ of the original activity. The fraction of the original activity remaining after succeeding half-lives is:

Activity after 1 half-life = ½ of the original
Activity after 2 half-lives = ½ x ½ = ¼ of the original
Activity after 3 half-lives = ½ x ½ x ½ = $(½)^3$ = 1/8 of the original
Activity after 4 half-lives = $(½)^4$ = 1/16 of the original
Activity after 5 half-lives = $(½)^5$ = 1/32 of the original
Activity after 6 half-lives = $(½)^6$ = 1/64 of the original
Activity after 7 half-lives = $(½)^7$ = 1/128 of the original

Therefore, the activity remaining after 7 half-lives is 1/128 or 0.8% of the original activity. After this time the number of radioactive atoms remaining will of course also be 1/128 of the original number. A useful rule of thumb for you to remember is:

After 7 half-lives the activity has decreased to about 1%, and after 10 half-lives to about 0.1% of the original activity.

This rule strictly only applies when you are dealing with huge numbers of atoms. For example, suppose we start with a million atoms of iodine-131. (This is a tiny fraction of a microgram.) The half-life of iodine-131 is 8 days, so that during the first 8 days half the atoms decay to xenon-131. After 16 days, only a quarter or 250,000 atoms of iodine-131 are left. After 80 days only about 0.1% (1000 atoms) of iodine-131 remain. The others have all decayed to xenon-131. Finally we get down to the last couple of iodine-131 atoms and who can tell us at what moment either of them will decay? Decay is a random process: predictions work only when they are averaged over many atoms.

If the relative activity is plotted against time in half-lives, a typical decay curve is obtained as shown below:

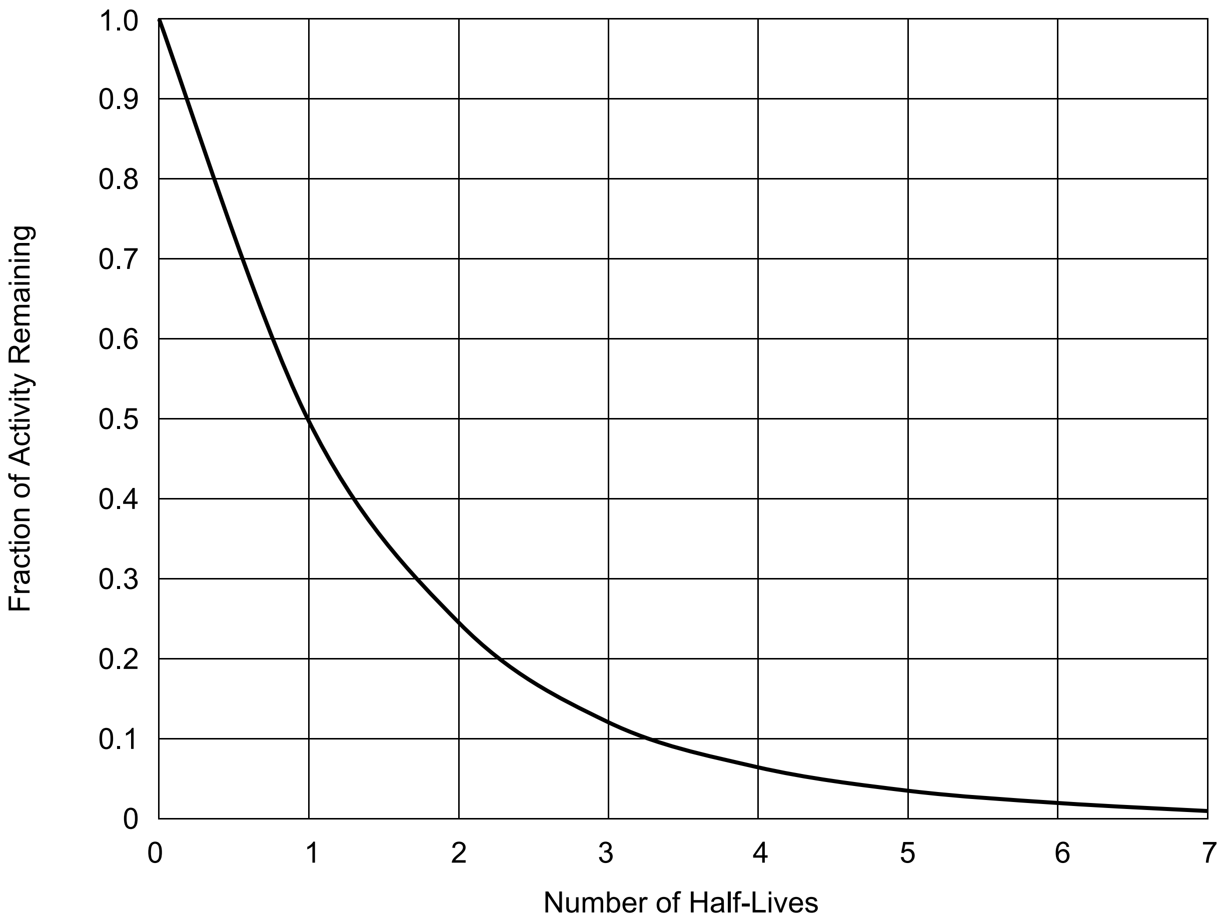


Fig. 2.23. Radioactivity Decay Curve

The decay curve shown plotted above has a linear Y-axis (the fraction of the activity that remains) and a linear X-axis (the number of half-lives). Linear in this sense means that the distance between equal intervals along the axis is always the same. You can see that such linear axes aren't much use to you once you get more than two or three half-lives along, because you can't see the small values well enough.

A smart way around this problem is to replot the graph with the Y-axis in a logarithmic scale rather than a linear scale. This means that the intervals on the Y-axis will be equal for each decade (i.e., 1% to 10%, or 10% to 100%. This compresses the vertical axis at the top and expands it at the bottom, so that the decay curve becomes a straight line. An easy way of doing this is to plot the curve on semi-log graph paper that has one of the two scales already set up as a logarithmic scale. An even easier way is for me to do it for you as in Fig. 2.24. You can now work out very easily the activity remaining after any period of decay for any radionuclide. Don't worry, we'll have an example in a minute.

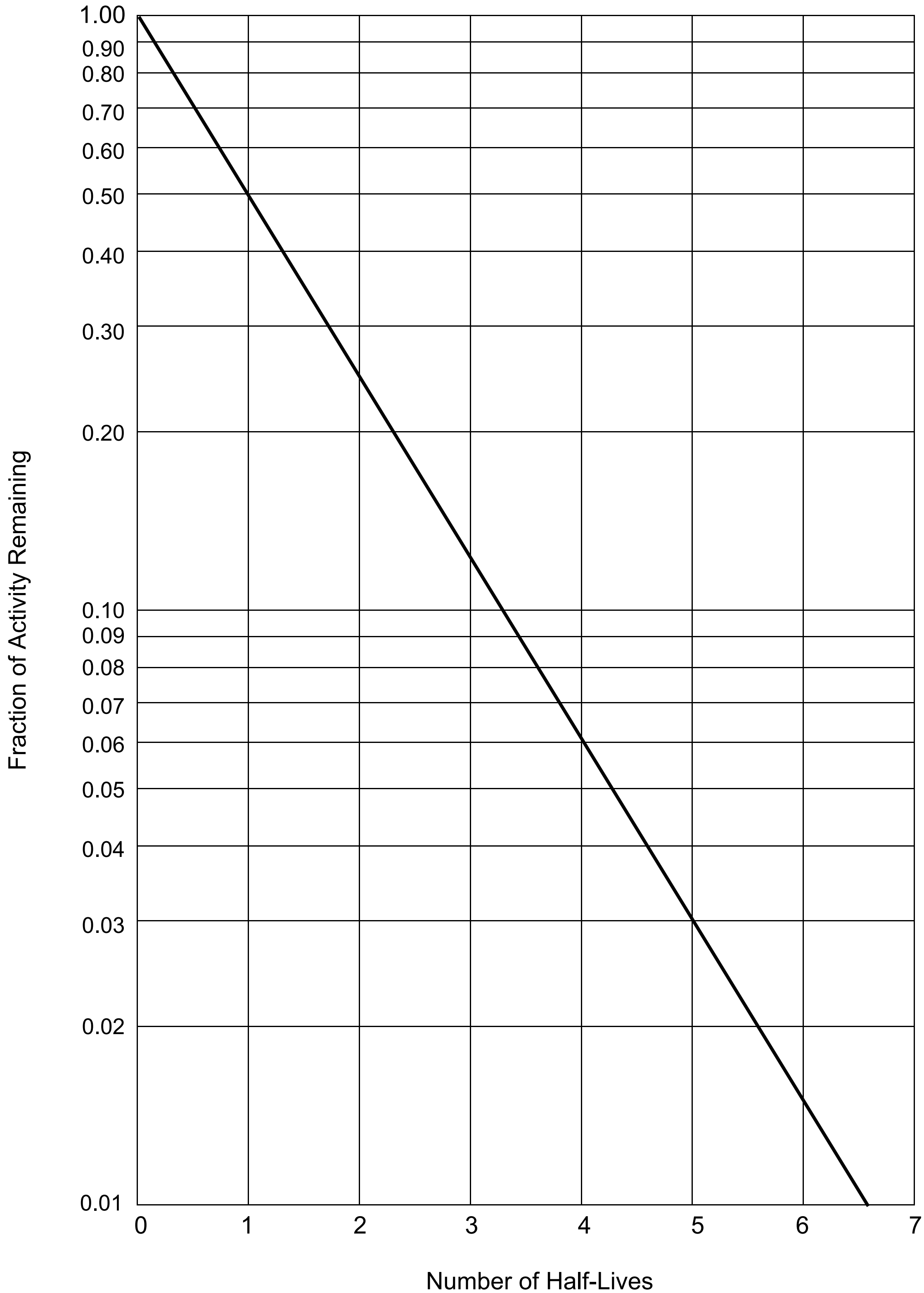


Fig. 2.24. Semi-Log Plot of Radioactive Decay Curve

Example

A laboratory tritium source with an activity of 100,000 disintegrations per second (dps) was bought 20 years ago. What activity remains now? (Tritium has a half-life of 12.3 years.)

Solution

We need to know the number of half-lives that has elapsed. This is 20/12.3 = 1.63 half-lives.

Find this position on the horizontal or X-axis of Fig. 2.24. The value on the vertical or Y-axis that corresponds to this point on the curve (I still call it that even though it's now a straight line) is just over 0.30, say 0.32.

Therefore, 0.32 of the original activity remains after 20 years. That is 0.32 x 100,000 dps, or 32,000 dps.

Try a couple more examples using the graph. The accurate (calculated) answers are on the right.

50,000 dps of Co-60 (half-life = 5.3 years) after 20 years	*(3,656 dps)*
10,000 dps of Cs-134 (half-life = 2 years) after 5 years	*(1,768 dps)*

When sources are used to calibrate lab equipment, you have to take into account the loss of activity with time. We use such calibration sources (called tritium standards) when we measure the tritium concentration in urine for dose measurements. You'll be pleased to hear that the Health Physics Lab Techs use a more sophisticated approach than the graph. If you want to know how it's done, check out the box below.

Self-luminous paints used in watches and instruments consist of a phosphor and a radioactive substance, e.g., tritium or radium. Some of the old watches used radium, but nowadays tritium is used because it emits no gamma. The beta particles from tritium have very low energy (18 keV) and can't penetrate through the watch, so there is no radiation hazard.

The reason I'm telling you this is that you may have noticed that your watch no longer glows as brightly in the dark as it used to. This is not due to your getting older and your eyes losing their sensitivity; it's merely the decay of the tritium causing a 50% drop in brightness every twelve years.

Watches contain about 7E7 Bq of tritium, and theatre exit signs about 1000 times more.

The activity of a source decreases by a factor of 2 in each half-life. After n half-lives, it will have decreased by a factor of 2^n. So the fraction of activity remaining after n half-lives, A_n is related to the activity at time 0, A_0 by the equation

$$A_n = A_0/2^n \quad \text{or } A_n = A_0 \times 2^{-n}$$

In the example above, n = 1.626. If you have a calculator that can deal with exponents, i.e. it can work out $2^{1.626}$, it'll tell you the answer is 3.0866. So you divide the original activity of 100,000 dps by 3.0866 to get 32,399 dps.

You can also do it the other way by multiplying 100,000 dps by $2^{-1.628}$. You'll get the same answer.

THE BECQUEREL: A UNIT OF ACTIVITY

Henri Becquerel was a Frenchman who discovered radioactivity in 1896, and the unit of activity is named in his honour. It is abbreviated as Bq with a capital B, but if you write it out in full (like "becquerel"), use a small "b". *)

1 becquerel represents one disintegration per second.

This is a rather small amount of activity, useful for environmental measurements. Sources in a nuclear plant often have much greater activity, and the following multiples are often used:

1 kBq (kilobecquerel)	= 1E 3 Bq
1 MBq (megabecquerel)	= 1E 6 Bq
1 GBq (gigabecquerel)	= 1E 9 Bq
1 TBq (terabecquerel)	= 1E12 Bq

If you have a source with an activity of 1 GBq, it must contain enough radioactive atoms to provide 1E9 disintegrations per second. A source with a long half-life will have a smaller fraction of its total number of atoms decaying per second than a short-lived source would. This means that to yield the same activity, a long-lived source will require many more atoms than a short-lived source. This is illustrated in the simple picture below.

1 GBq Fe-59	1 GBq Pu-239	1 GBq U-238
$T_{1/2}$ = 44 d	$T_{1/2}$ = 24000 y	4.5E9 y
0.54 µg	0.45 g	81 kg

Fig. 2.25. How Much You Need for 1 GBq

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*) This is standard practice. If a unit is named after a person, it is written in lower case, and the first letter of the symbol abbreviation is written in upper case. For instance, sievert and Sv, gray and Gy, watt and W, ampere and A, etc. But metre and m, kilogram and kg, second and s, because they aren't named after a person.

The relationship between half-life and the amount of a radionuclide required to give an activity of one GBq is shown in Table 2.3.

This illustrates that the longer the half-life, the greater the quantity of radionuclide needed to produce the same activity. Of course, the longer-lived substance will remain radioactive for a much longer time.

TABLE 2.3. MASS FOR 1 GBq ACTIVITY

Radionuclide	*Mass for 1 GBq*	*Half-Life*
Nitrogen-16	2.7E-13 g	7.1 s
Aluminum-28	9E-12 g	2.2 min
Iodine-131	2.2E-7 g	8 days
Manganese-54	3.5E-6 g	313 days
Cesium-137	3.1E-4 g	30 years
Radium-226	0.03 g	1600 years
Thorium-232	247 kg	1.4E10 years

For example, nitrogen-16 with a half-life of 7 seconds will have decayed almost completely in a minute or so. Uranium-238, however, will still be about as active after a million years as it was today.

Some Neat Mathematical Stuff:

The **decay constant**, λ, (Greek letter lambda) is the fraction of atoms decaying per second. So if you have n atoms of any particular radionuclide, λn of them will decay in each second.

$$\lambda = \frac{0.69}{T_{1/2}}$$

where $T_{1/2}$ is the half-life in seconds. In the exercise on page 38, λ was 0.1. The exact half-life was 6.9 seconds.

What fraction of iodine-131 decays each second? The half-life is 8 days. First you have to convert this to seconds: now 8 days

= 8 x 24 x 60 x 60 s = 691,200 s = 0.69E-6 s.

$$\lambda = \frac{0.69}{T_{1/2}} = \frac{0.69}{0.69\text{E-}6} = 1\text{E-}6$$

In other words one in a million will decay each second.

The number of atoms in a sample can be calculated from **Avogadro's Number, N_0**.

N_0 = 6.022 E26 atoms per mole, and a mole is the atomic mass in kg.

Going back to our iodine-131 example, this means that 131 kg of iodine would contain 6E26 atoms of I-131.

This is how I calculated the masses for 1 GBq in Table 2.3.

The activity of a source = nλ, where n is the number of atoms in the source. This means n = (activity)/λ.

In our 1 GBq iodine-131 example,

n = 1E9/1E-6 = 1E15 atoms of I-131.

Since 131 kg of I-131 will contain 6E23 atoms, we can work out that 1E15 atoms will weigh

$$131\text{ kg} \times \frac{1\text{E}15}{6\text{E}22} = 2.18\text{E-}10\text{ kg} = 0.22\ \mu\text{g}.$$

NEUTRONS

The discovery of neutrons in 1932 paved the way for the large-scale uses of nuclear energy today. The radioactivity produced in nuclear reactors is entirely due to neutron reactions with the materials in the reactor core.

A neutron (symbol: n or $_0n^1$) has about the same mass as a proton (1 amu), but unlike a proton, it has no electrical charge.

A proton with its positive charge is strongly repelled when it approaches a positively charged nucleus — you will recall that like charges repel.

Fig. 2.26. A Proton is Repelled, But a Neutron is Not

Neutrons have no charge, are not repelled when they approach nuclei, and can actually enter nuclei. It is for this reason that they are of great importance in nuclear physics — if you like, they are the scalpel with which the physicist can poke around in the nucleus. Since neutrons are electrically neutral, they cause no ionisation directly, and so they can travel great distances through matter, much like gamma rays.

The only way to produce neutrons is to knock them out of nuclei. They emerge from the nucleus with a high speed, having energies of up to several MeV. Most of these neutrons are slowed down by collisions with nuclei. After perhaps a hundred of such collisions, the speed of the neutrons is reduced to such an extent that they have about the same kinetic energy (energy of motion) as the atoms of their surroundings.

The kinetic energy of these atoms is based on the temperature of the material they form. That is why neutrons that have slowed down to the same energy levels of the surrounding atoms are called **thermal** neutrons. They are the most useful for causing fission. Thermal neutrons continue to bounce around until they are captured by some nucleus.

The way in which neutrons interact with matter depends to a large extent on their energies. For this reason, neutrons are often classified by energy as follows:

Fast Neutrons	- above 8 keV
Slow Neutrons	- below 8 keV
Thermal Neutrons	- about 0.025 eV

Although the energy of thermal neutrons is as low as it can be, you mustn't get the impression that thermal neutrons are loitering about. They still travel at 2.2 km/s.

NEUTRON SOURCES

There are three main sources of neutrons in CANDU reactors.

1. Fission

Besides the methods of decay discussed previously, there is yet another way in which heavy nuclei such as uranium can reach a stable state. This is by splitting into two parts. The splitting of a nucleus is called **fission**, and the two parts of the original nucleus are called **fission fragments**. (The word fission was borrowed from the biologists, who use it to describe cell division.) These fission fragments are nothing other than two smaller nuclei. Spontaneous fissioning of uranium happens relatively infrequently, occurring only about seven times a second in one kg of uranium.

However, toward the latter part of the 1930's it was discovered that U-235 could be induced to fission by thermal neutrons. A neutron may enter the U-235 nucleus to form an excited compound nucleus, U-236*. (The asterisk * indicates the excited state.)This nucleus fissions, and beside the fission fragments, it also produces one to three additional neutrons, and a great deal of energy in the form of heat and gamma radiation.

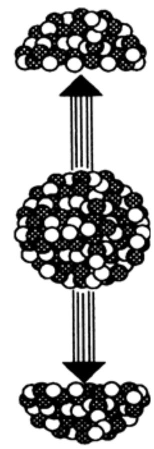


Fig. 2.27. Fission

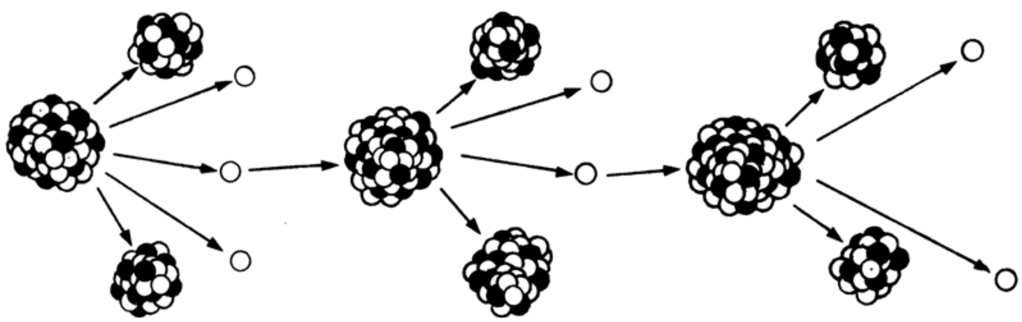


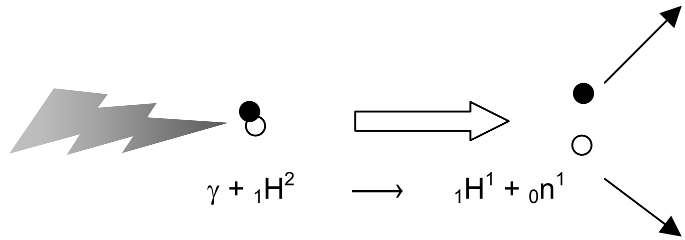
Fig. 2.28. A Chain Reaction

The production of additional neutrons in each fission is very important. If these extra neutrons can be made to react with other U-235 nuclei to produce still more fissions, so that each fission results in additional fissions, a "self-sustaining" or **chain reaction** occurs as shown above. This does happen when the right conditions are provided. These conditions are discussed in the Nuclear Theory courses.

The fission neutrons cover a wide energy range, but have an average initial energy of about 2 MeV. Fission neutrons lose energy through collisions with the fuel, pressure tubes, structural material and moderator. When the reactor is shutdown, this source of neutrons disappears.

2. Photoneutrons

Gamma photons with energies greater than 2.21 MeV can interact with the deuterium nuclei in heavy water to produce so-called **photoneutrons**.



$$\gamma + {}_1H^2 \longrightarrow {}_1H^1 + {}_0n^1$$

Fig. 2.29. Photoneutron Production With Deuterium

In CANDU reactors, this reaction occurs wherever deuterium (in heavy water in the reactor) is being zapped by high energy gamma radiation. When the reactor is shut down, the photoneutron production decreases but doesn't stop. The remaining fission product activity in the fuel will last long enough to provide enough gamma photons to cause photoneutrons to be registered by the reactor instrumentation for as long as three or four months after shutdown.

3. Neutron Sources Used for Calibration

All nuclear stations have a neutron source for calibrating neutron instrumentation.

If an alpha emitter, such as americium-241, is mixed with beryllium, the alpha particles emitted by Am-241 can cause this reaction:

$$_2He^4 + {}_4Be^9 \longrightarrow {}_6C^{12} + {}_0n^1$$

Because of the short range of the alpha particles, the americium must be closely mixed with the beryllium. We have two sources like this; one for calibrating the reactor start-up instrumentation (2.2E4 neutrons/second) and one for checking the neutron survey meters (2.3E6 n/s).

NEUTRON REACTIONS

The interactions of neutrons with nuclei are called NEUTRON REACTIONS.

Neutrons emitted from neutron sources are fast neutrons. Either they will be captured by nuclei in their paths, or more likely they will be slowed down first and then captured. The most common neutron reactions are:

1. Fission
2. Scattering
3. Activation

1. Fission

We have already discussed this under the heading of Neutron Sources a couple of pages ago.

2. Neutron Scattering Reactions

(a) Elastic Scattering

A neutron collides with a nucleus, loses some energy and bounces off in a different direction. This resembles a billiard ball type of collision. The fraction of its initial energy the neutron loses depends on how it hits the target nucleus. Just like on a pool table: if the cue ball makes only

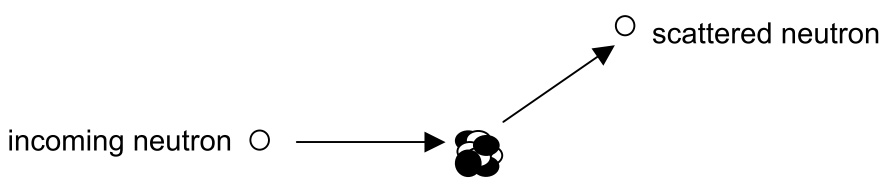


Fig. 2.30. Elastic Scattering

a glancing blow, it will lose very little energy. The energy lost by the neutron is gained by the target nucleus that now takes off at high speed leaving its cloud of electrons behind. The positively charged nucleus produces ionisation much like an alpha particle does.

Light nuclei are the most effective for slowing down neutrons. A neutron colliding with a heavy nucleus rebounds with negligible loss of speed and loses essentially no energy: rather like firing a cue ball at a cannon ball. On the other hand neutrons will not be scattered by the electrons surrounding a nucleus, but will travel straight on much like baseballs through a fog.

(b) Inelastic Scattering

A neutron may strike a nucleus and, instead of bouncing off as in elastic scattering, it may form a "compound nucleus". This will be in an excited state and will attempt to become stable by emitting a neutron of lower energy, together with a gamma photon that will take the remaining energy. This process is known as **inelastic scattering**.

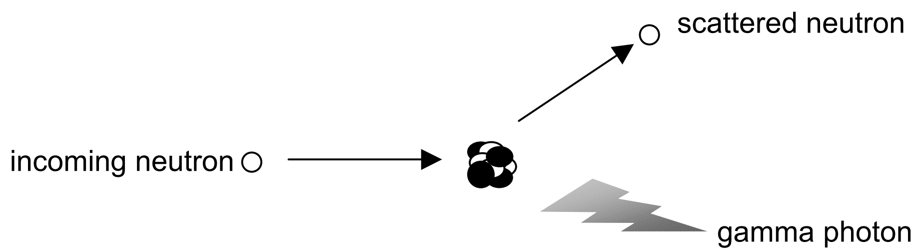


Fig. 2.31. Inelastic Scattering

Generally, inelastic scattering does not occur unless neutrons of energy greater than 100 keV are colliding with heavy atoms. Therefore, we would expect this reaction to occur in the uranium fuel, but not in the D_2O moderator. Why?

3. Neutron Activation Reactions

A neutron strikes a nucleus and is again captured to form a compound nucleus. This is too energetic to be stable, and it will now do one of two things. Either it immediately coughs up either a proton or an alpha particle to form a new nucleus of a different element, or the compound nucleus can spit out a gamma photon to get rid of the excess energy. In the second case, since it keeps the incident neutron, the nucleus forms a different isotope of the same element.

Which of these reactions occurs depends on the energy incident neutron and on which nuclide it hits. Examples of each of these reactions are given below

(a) Neutron-Proton Reaction (n,p)

Oxygen-16 is a good example. It captures a high-energy neutron and emits a proton to form nitrogen-16. This is known as an **(n,p) reaction**, because a neutron goes in and a proton comes out.

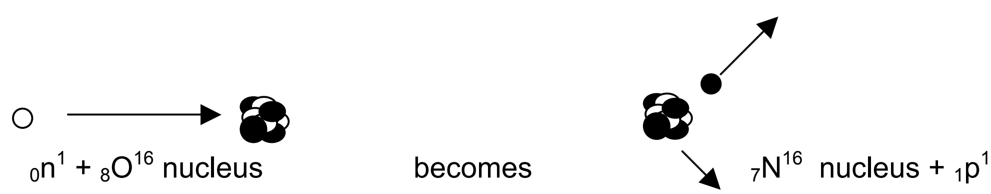


Fig. 2.32. (n,p) Reaction of Oxygen-16

The product, nitrogen-16, is radioactive. It is a beta-gamma emitter with a half-life of 7.2 s. What is much more important is that it also emits very high-energy gamma photons in the range of 6 to 7 MeV. At power, these gamma photons emitted by the N-16 that was created by (n,p) reactions with oxygen atoms in light or heavy water are important in radiation protection.

(b) Neutron-Alpha Reaction (n,α)

An example is the slow neutron capture by boron-10 in this reaction:

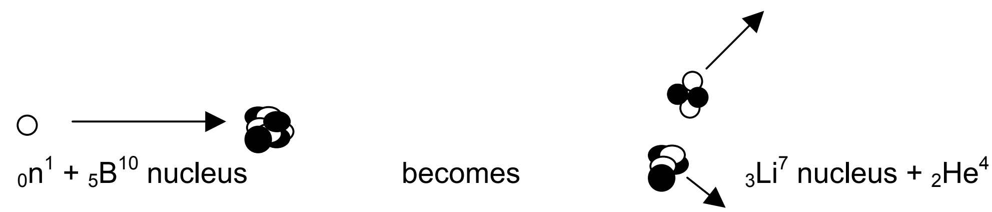


Fig. 2.33. (n,α) Reaction of Boron-10

Both the alpha particle and the lithium nucleus have kinetic energy, and both cause ionisation in the usual way. This is an important reaction for instruments used to detect slow and thermal neutrons.

(c) Neutron-Gamma Reaction (n,γ)

This is one of the most common neutron reactions. The new nucleus formed emits only a gamma photon. This means that the product nucleus is an isotope of the same element as the original nucleus (its mass number will have increased by one). Most elements will undergo such reactions, but the reaction is much more likely to occur with thermal neutrons than with fast neutrons. This reaction is often called **radiative capture** because a gamma photon is **radiated** when the neutron is **captured**. There are many examples; we'll use just four.

1. The simplest neutron-gamma reaction (n,γ) occurs with hydrogen-1 to produce deuterium (hydrogen-2) in $_0n^1 + {}_1H^1 \longrightarrow {}_1H^2 + \gamma$:

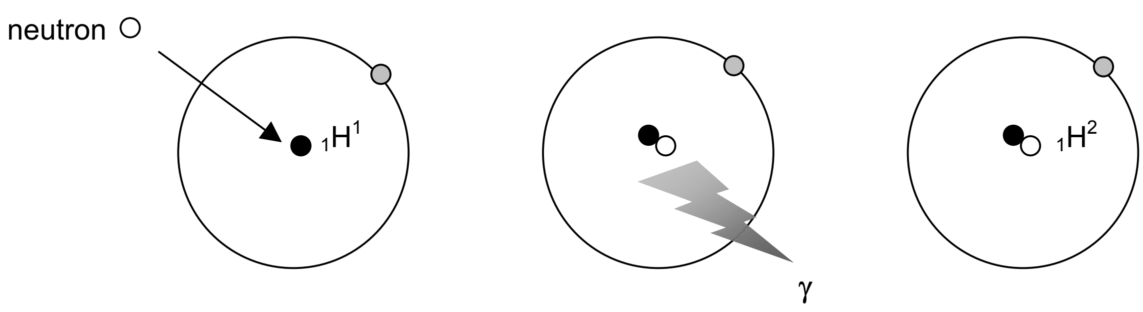


Fig. 2.34. (n,γ) Reaction in H-1 to Produce H-2

The deuterium formed is a stable nuclide. However, most products of (n,γ) reactions are radioactive and are beta-gamma emitters.

2. Deuterium itself can go through an (n,γ) reaction as in ${}_0n^1 + {}_1H^2 \longrightarrow {}_1H^3 + \gamma$:

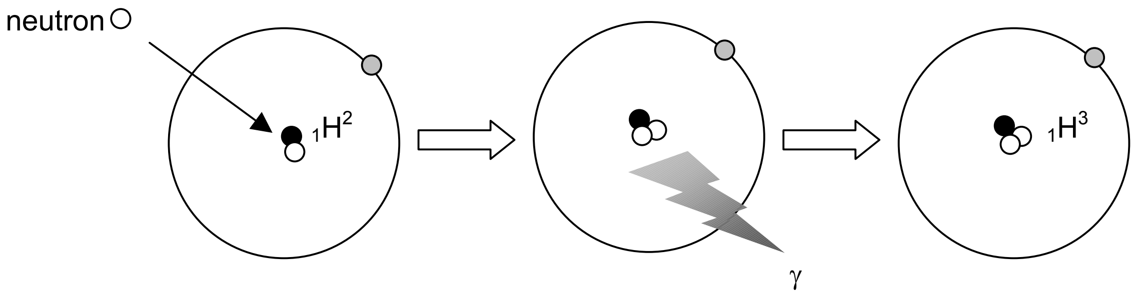


Fig. 2.35. (n,γ) Reaction in H-2 to Produce H-3

The product is the hydrogen isotope with a mass of three. This seems an appropriate stage to review the three hydrogen isotopes briefly:

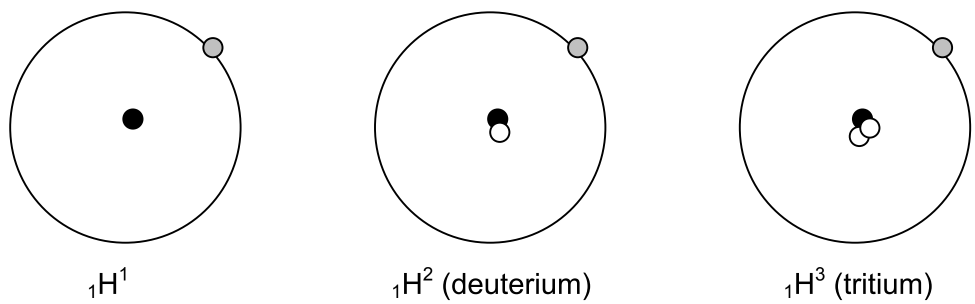


Fig. 2.36. The Three Isotopes of Hydrogen

All three atoms are isotopes of hydrogen and therefore their nuclei each contain one proton. Besides this, the deuterium nucleus contains one neutron, and the tritium nucleus contains two neutrons. Chemically all three isotopes are identical, but hydrogen and deuterium are stable; tritium is radioactive.

Tritium has a half-life of 12.3 years. It emits beta particles of low energy (maximum energy = 18 keV):

$${}_1H^3 \longrightarrow {}_2He^3 + \beta^- \text{ (no gamma is emitted)}$$

Tritium is formed in heavy water reactors where deuterium is exposed to slow neutrons. It is a very important radionuclide in CANDU reactors. At Point Lepreau, about one third of the radiation exposure to the staff is from tritium.

3. An important (n,γ) reaction is that undergone by argon-40:

$${}_0n^1 + {}_{18}Ar^{40} \longrightarrow {}_{18}Ar^{41} + \gamma$$

Argon-41 is a beta-gamma emitter with a half-life of 1.8 hours. Since argon makes up almost 1% of air, radioactive argon-41 is going to be produced in all places where air is exposed to neutrons, for example in the Fuelling Machine Vaults located at the ends of the reactor.

4. As a last example, consider the (n,γ) reaction of U-238 in the nuclear fuel:

$$ {}_{0}n^{1} + {}_{92}U^{238} \longrightarrow {}_{92}U^{239} + \gamma $$

The product U-239 is a β^-,γ emitter with a half-life = 23 minutes.

$$ {}_{92}U^{239} \longrightarrow {}_{93}Np^{239} + \beta^-, \gamma $$

The daughter is an element of atomic number 93 called neptunium (Np) which does not exist in nature. Np-239 is also a beta-gamma emitter and it has a half-life of 2.3 days:

$$ {}_{93}Np^{239} \longrightarrow {}_{94}Pu^{239} + \beta^-, \gamma $$

The daughter is plutonium-239, another element which does not occur naturally. Pu-239 is a long-lived alpha-emitter. It has nuclear properties somewhat similar to uranium-235, because neutrons can cause it to fission. Fuel that is in an operating reactor will gradually build up some Pu-239 as a result of the reactions above, and then this Pu-239 will fission and create heat just like U-235. By the time a typical fuel bundle is taken out of the reactor at Point Lepreau, perhaps 40% of all the fissions have been provided by the Pu-239 that was made by radiative capture of U-238. Who said that there was no free lunch?

NEUTRON REACTIONS IN TISSUE

The harmful consequences of various radiations are ultimately due to their ability to deposit energy in living tissue. Ionisation is probably the most important way in which they do this.

Alpha and beta particles produce ionisation directly. Gamma rays produce ionisation indirectly by the methods described earlier (pages 23 - 25). Neutrons also produce ionisation indirectly; they do this by the various interactions we have considered since page 47.

Fast Neutrons

The human body is composed largely of water (about 60% by weight) and this of course contains many hydrogen nuclei. In fact, although the hydrogen in the body accounts for only about 10% of its weight, well over half the atoms (63%) are hydrogen atoms. (Just in case you have a burning desire to know, there are about 1.5E27 hydrogen atoms in the average guy.) If you paid attention when we were talking about elastic scattering, you will appreciate that fast neutrons are slowed down most effectively in these reactions when they collide with light nuclei in tissue. That's the hydrogen atoms.

Much of the kinetic energy of the neutron is transferred to the hydrogen nucleus (i.e., the proton) it collides with. The fast proton produced in this way generates ionisation in its path. Because protons have a much greater mass than electrons, they produce a much denser ion trail. The general effect is rather similar to that produced by alpha particles.

In the meantime the incident neutron has lost the energy it gave to the proton. It may lose enough energy in further elastic collisions to finally become a slow neutron, when some of the nuclear reactions discussed earlier become possible.

Slow and Thermal Neutrons

Slow neutrons undergo (n,γ) reactions with many of the elements in the body, particularly hydrogen:

$$_0n^1 + {_1H^1} \longrightarrow {_1H^2} + \gamma$$

The gamma photon produced always has energy of 2.2 MeV and it will cause indirect ionisation via the photoelectric and Compton effects. Therefore when neutrons are absorbed by (n,γ) reactions in the body, the body tissues will be irradiated by gamma radiation. This is over and above the abuse they have suffered in slowing the neutrons down.

When slow neutrons are absorbed by a nucleus in radiative capture, the product nucleus will be an isotope with one more neutron than the original target nucleus. Obviously. A few of these new nuclides will be radioactive, and so will add further insult to injury. The good news is that the dose contributed by these radionuclides is negligible compared to that contributed by the neutrons themselves.

ACTIVATION AND CONTAMINATION

Generally speaking, the only naturally occurring radioactive substance to be found in a nuclear power station is the uranium in the fuel. However, as a result of operation (i.e., fission), the fuel and, to a lesser extent, many of the systems in the station will become radioactive. The systems may have been made radioactive by **activation** or **contamination**. So, before we go any further, let's understand the difference between these terms.

Activation

An object is normally not made radioactive by being subjected to alpha, beta or gamma radiation. Yet it can be made radioactive if neutrons irradiate it. It is then said to be **activated**: the process is called **activation**. On pages 49 to 52 we discussed how normally stable atoms can become activated, i.e., made radioactive by neutron absorption.

> **Neutron activation analysis** exploits this principle: a sample is irradiated with neutrons, and the resulting activated nuclei are identified from their gamma decay energies. Concentrations of parts per billion can be measured.
>
> A common use of activation analysis is in testing highly purified substances for traces of impurities (e.g., in the manufacture of semiconductor devices). It is also widely used in forensic analyses: the source of paint, mud, hair, drugs, etc., can be clearly identified from the trace elements the samples contain.

Contamination

Objects may become radioactive in an entirely different manner. If someone has spilled some radioactive liquid on the floor, and you step in it, the sole of your shoe will undoubtedly be radioactive (it won't smell any worse than before, though). The atoms of the shoe will not be radioactive themselves, but the surface of the shoe will appear to be radioactive because of the radioactivity from the liquid that is attached to it. We say that such an object is **contaminated**. We can now define what we mean by contamination at Point Lepreau:

RADIOACTIVE CONTAMINATION is the presence of radioactive material in any place where it is not supposed to be.

It is obvious that contamination is quite a different thing from activation. For example, the heavy water coolant (and any impurities it contains) can have radioactive material produced in it by activation; but the pump that circulates it is not exposed to neutrons and therefore does not become radioactive by activation. However, while the coolant is circulating through the pump it will deposit radioactive material on various parts of the pump. If the pump has to be stripped down, it will be found to be radioactive because of this contamination—we'll have to remove the contamination before we can work safely on the pump.

RADIATION FROM THE REACTOR CORE

While several of the systems of a reactor can become quite radioactive, the reactor core itself is by far the most radioactive source. For this reason the reactor is completely surrounded by a protective shield which is very thick. We have already mentioned earlier that protection from alpha particles is a relatively simple matter. The same is largely true for beta radiation.

The absorption of neutrons and gamma rays is much more difficult, because they are much more penetrating. Both are produced in vast numbers in the reactor core while it is operating. From a radiation protection point of view, it is useful to make the distinction between radiation sources that are present only when the reactor is at power, and those that are still present even when the reactor is shut down. There are six sources present at power, and three of them are still there after shutdown.

RADIATION SOURCES PRESENT AT POWER

1. Neutrons Produced by the Fission Process

On average, 2.5 fast neutrons are released in each fission. Their average energy is high at around 2 MeV. They lose this energy by colliding with the atoms of the materials in the reactor (e.g., fuel, coolant heavy water, pressure tubes, calandria tubes, and moderator heavy water). When the reactor is shut down, these neutrons disappear because fission stops.

2. Prompt Fission Gamma Rays

Gamma rays are emitted at the instant of fission. These are called **prompt fission gamma rays**, and the sum of their energies amounts to about 5 MeV per fission. When the reactor is shut down, they disappear because there are no fissions.

3. Neutron Capture Gamma Rays

All the materials in the reactor core will capture neutrons to some extent to produce excited nuclei, as in the (n,γ) capture process we discussed on pages 50 to 52. The excited nuclei each emit one or more gamma photons — these gamma photons are called **capture gammas**. Some of the in-core materials producing capture gammas are fuel, fuel sheaths, pressure tubes, calandria tubes, coolant and moderator. Some examples:

$$ {}_{0}n^{1} + {}_{92}U^{238} \longrightarrow {}_{92}U^{239} + \gamma $$

$$ {}_{0}n^{1} + {}_{40}Zr^{91} \longrightarrow {}_{40}Zr^{92} + \gamma $$

$$ {}_{0}n^{1} + {}_{28}Ni^{60} \longrightarrow {}_{28}Ni^{61} + \gamma $$

The first product nuclide (${}_{92}U^{239}$) is radioactive, the other two happen to be stable. In each case, the production of capture gammas stops when the reactor is shut down, because there is no source of neutrons.

In addition to the above sources, which are present only when the reactor is operating, many sources will be found in a reactor after it has been operating for some time. These will be emitting radiation whether the reactor is operating or shut down. The main ones are:

4. Fission Products

Each fission produces two fission fragments. They are simply nuclei of intermediate size, which decay by β^-,γ emissions.

The fragments formed directly by fission and all the daughters formed by the decay of the fragments are collectively called FISSION PRODUCTS.

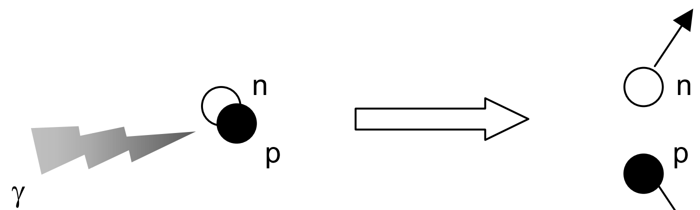
The fission products make the fuel elements extremely hot sources, even after they have been out of the reactor for a long time. We'll deal with them separately in a moment.

5. Activation Products

These are the radioactive atoms produced by (n,γ), (n,p), and (n,α) reactions. They have varying half-lives, depending on the radionuclide, and are mainly β^-,γ emitters. For us, the most important activation product is tritium. Again, we'll deal with activation products separately a couple of pages further along.

6. Photoneutrons

Deuterium nuclei, which absorb gamma photons of energy 2.21 MeV or greater, will emit neutrons. We met this reaction before on page 47, i.e.,



$$\gamma + {}_1H^2 \longrightarrow {}_1H^1 + {}_0n^1$$

Fig. 2.37. (γ,n) Reaction With Deuterium

Therefore, photoneutrons will be produced if the moderator or coolant is heavy water. When the reactor is at power, high-energy gammas will be generated by (a) fission, (b) capture gamma from radiative capture, (c) fission products, and (d) activation products. When the reactor is shut down, the gamma photons still being emitted by both fission products and activation products will maintain the production of photoneutrons, although at a decreased level.

At Power	Shut Down
a	-
b	-
c	c
d	d

The whole core is normally contained in a leak-tight vessel, which in turn is in a shielded area, so that radiation sources in the core do not prevent work in accessible areas during normal operation and during shutdown.

FISSION PRODUCTS

Each fissioning nucleus produces two fission fragments that are nuclei of intermediate mass. The fission fragments are radioactive. Fuel elements that have been in an operating core contain zillions of these fragments and their daughters, and they are extremely hazardous to your health. And you thought cigarettes were bad!

If every atom of U-235 were to split up in exactly the same way, we would have only two kinds of fission fragments. However, U-235 atoms can fission in more than 40 different ways to yield over 80 different fission fragments. The two fragments that result from a fission are rarely equal in size. Normally, one fragment has about 1½ times the mass of the other one.

Fig. 2.38 shows that the fission fragments tend to fall into two groups, a light group at mass of about 95 and a heavy group at mass of about 140. You'll see from this diagram that symmetrical fission with both fragments having equal mass is very rare (about 1 in 10,000 times).

Let us consider a typical fission reaction for U-235. Likely fission fragments are strontium and xenon with atomic numbers of 38 and 54 respectively. Assume that two neutrons are emitted in the fission, so that the equation is:

$$ {}_{0}n^{1} + {}_{92}U^{235} \longrightarrow {}_{38}Sr^{95} + {}_{54}Xe^{139} + 2{}_{0}n^{1} + \gamma $$

You will note that the sum of the number of neutrons and protons on the left (before fission) is equal to the sum on the right (after fission).

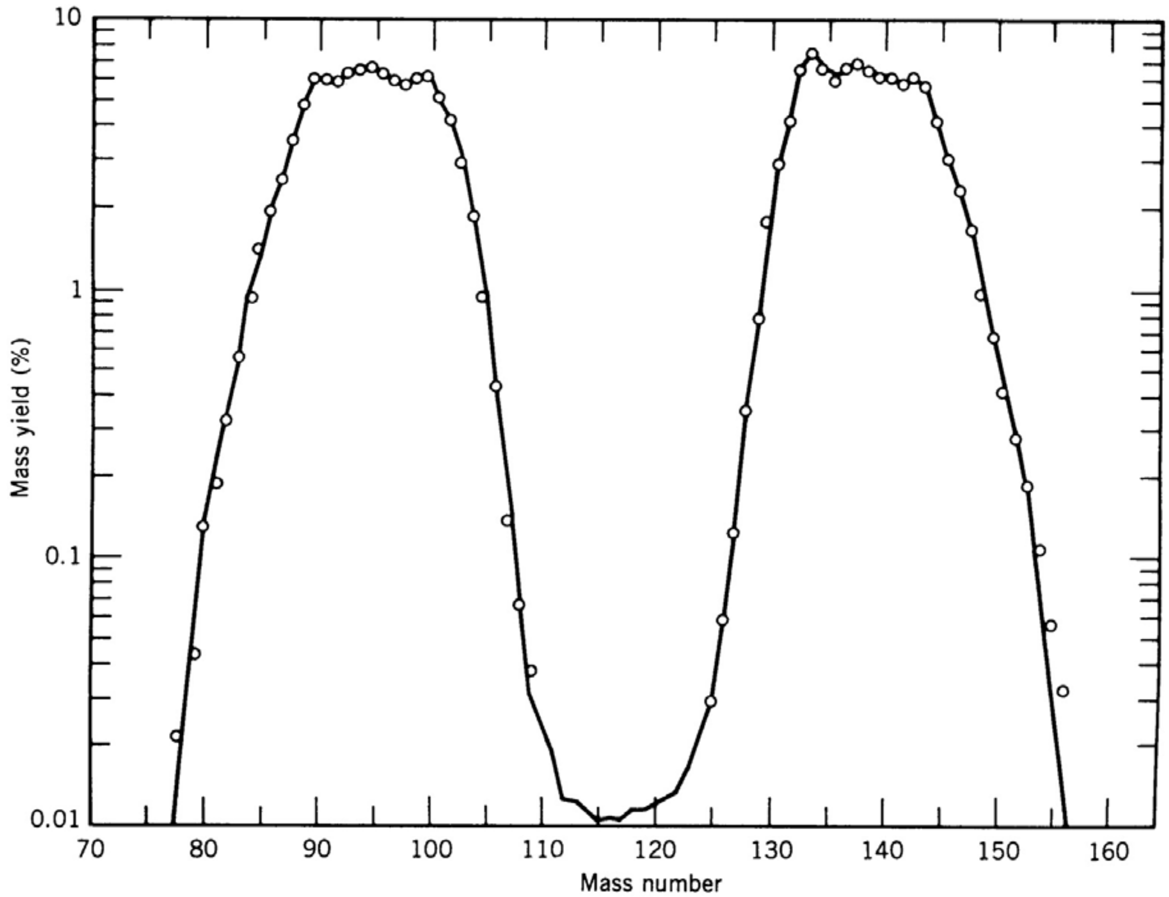


Fig. 2.38. Fission Fragment Yield for U-235

Another example of U-235 fission producing different products is:

$$ {}_{0}n^{1} + {}_{92}U^{235} \longrightarrow {}_{39}Y^{97} + {}_{53}I^{136} + 3{}_{0}n^{1} + \gamma $$

Uranium has a higher neutron-proton ratio than the stable elements of about half its mass. Despite the fact that each uranium fission liberates one to three neutrons, the smaller fission fragments will still have too many neutrons to be stable, and they will therefore be radioactive. Since beta decay is the result of a neutron changing to a proton, the fission fragments will practically all be beta/gamma emitters. (We are talking here of beta minus decays, right?)

And do remember that all the tribes of fission fragments, and the daughters they produce by their beta decays, and all the granddaughters begat by the daughters, and all the great-grand-daughters begat by the ...etc., collectively are called fission products.

The further decay of each fission fragment is termed a **fission decay chain** and, on the average, involves about three successive beta decays until a stable neutron-proton ratio is reached. Two examples of fission decay chains are:

$${}_{38}Sr^{94} \xrightarrow{\beta^-,\gamma} {}_{39}Y^{94} \xrightarrow{\beta^-,\gamma} {}_{40}Zr^{94}$$

$${}_{54}Xe^{140} \xrightarrow{\beta^-,\gamma} {}_{55}Cs^{140} \xrightarrow{\beta^-,\gamma} {}_{56}Ba^{140} \xrightarrow{\beta^-,\gamma} {}_{57}La^{140} \xrightarrow{\beta^-,\gamma} {}_{58}Ce^{140}$$

In all, about 600 fission products have been identified. Most of them of course emit gamma photons as well as beta particles.

The half-lives of fission products vary from a fraction of a second to thousands of years. A tremendous amount of fission product activity is built up in the fuel of a reactor after even a few days of operation.

It is the high fission product activity that requires us to cool fuel removed from the reactor. Otherwise the β and γ decay energy absorbed by the fuel itself would be sufficient to melt it. Bad scene.

The rate at which fission occurs is proportional to reactor power. To shut the reactor down, neutron absorbers are introduced into the core so that more neutrons are absorbed than the fission chain reaction can reproduce. The neutron population decreases and fission stops. This means no new fission fragments are produced, but most of the fission products that were produced by decay from previous fission fragments are still there.

Fig. 2.39 opposite shows how the radiation from fission product activity decreases with time after a fuel bundle is removed from the reactor. You can see that initially the intensity of the radiation drops rapidly with time. For example, one hour after the bundle has been removed from the core, the radiation field at one metre from the side of it is almost 1000 gray per hour. (This is bad news: you stand there for half a minute, and you're history.) However, if you let the radiation field decay away for six months, it would be down to 10 Gy/h, and after two years, it is only 1 Gy/h. (We'll tell you what a gray is in the next chapter.)

It seems that the radiation field from the fuel bundle decreases very quickly at first, and then decreases more slowly as the months and years go by. In effect, it appears that the half-life of the activity in the fuel bundle increases from hours to years. This is quite true: after the short-lived fission products have decayed, only the longer-lived fission products remain—they'll take a long time to decay and so will the radiation fields that they produce.

FUEL FAILURE

The uranium dioxide fuel is encased in zircaloy sheathing. Sometimes the fuel element sheathing develops cracks or small holes. We call this **fuel failure**; it allows fission products to escape from such defective fuel elements and contaminate the heat transport system.

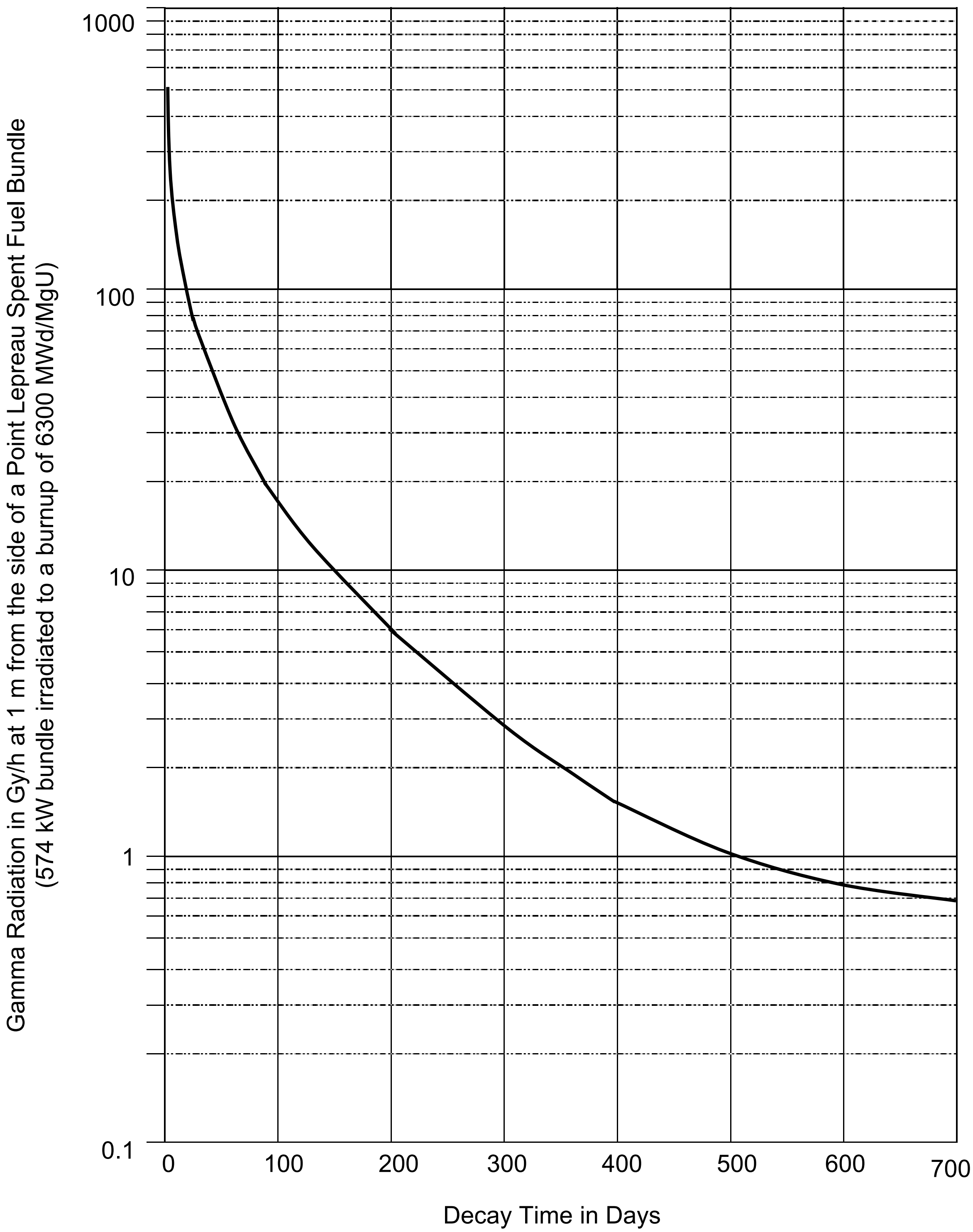


Fig. 2.39. The Decrease in Fission Product Activity with Time

Some fission products that have a tendency to escape from defects are the fission product gases xenon and krypton, iodine, and soluble elements, such as cesium.

After a fuel failure, if the primary heat transport system has any leaks (e.g., in valve packing and pump seals) or is opened up, the radioisotopes of xenon, krypton, and iodine escape into and contaminate the air. These radionuclides or their active daughters then become a hazard to those breathing this air. A few of them are listed below, along with their half-lives and decay schemes.

$$_{53}I^{131} \xrightarrow[8\ d]{\beta^-,\gamma} {}_{54}Xe^{131}$$

$$_{53}I^{133} \xrightarrow[21\ h]{\beta^-,\gamma} {}_{54}Xe^{133} \xrightarrow[5\ d]{\beta^-,\gamma} {}_{55}Cs^{133}$$

$$_{53}I^{135} \xrightarrow[7\ h]{\beta^-,\gamma} {}_{54}Xe^{135} \xrightarrow[9\ h]{\beta^-,\gamma} {}_{55}Cs^{135} \xrightarrow[2E6\ y]{\beta^-,\gamma} {}_{56}Ba^{135}$$

$$_{36}Kr^{88} \xrightarrow[3\ h]{\beta^-,\gamma} {}_{37}Rb^{88} \xrightarrow[18\ min]{\beta^-,\gamma} {}_{38}Sr^{88}$$

$$_{52}Te^{138} \xrightarrow[1.4\ s]{\beta^-,\gamma} {}_{53}I^{138} \xrightarrow[6.4\ s]{\beta^-,\gamma} {}_{54}Xe^{138} \xrightarrow[14\ min]{\beta^-,\gamma} {}_{55}Cs^{138} \xrightarrow[32\ min]{\beta^-,\gamma} {}_{56}Ba^{138}$$

> One thing you might notice: in such fission product decay chains the half-lives of the daughters and their daughters, etc., usually become progressively longer. The reason for this is that the initial fission fragments have a lot of excess energy; this is reflected in a short half-life. As the excess energy diminishes in successive decays, the whole thing becomes less urgent from the radionuclide's point of view, and so the half-lives increase.

ACTIVATION PRODUCTS

While the reactor is operating, the moderator and the coolant are exposed to intense neutron irradiation in the core. As a result, many new nuclei are formed by (n,γ), (n,α), and (n,p) reactions with atoms of the materials in the reactor core. Most of these new nuclides are radioactive, although some are stable. We call the radioactive ones **activation products**.

> **ACTIVATION PRODUCTS are the radionuclides formed by (n,γ), (n,α) and (n,p) reactions.**

Any components inside a power reactor core will become intensely radioactive. When such components need to be maintained or replaced (like pressure tubes), they represent an enormous radiation hazard. Neutron activation is very important in the heavy water and the structural materials containing it in the core. Let's look at both the moderator and the coolant.

The Moderator System

The most important activation products are tritium (hydrogen-3), nitrogen-16, oxygen-19, and cobalt-60. They are produced by the following reactions:

$$_0n^1 + {}_1H^2 \longrightarrow {}_1H^3 + \gamma$$

$$_0n^1 + {}_8O^{16} \longrightarrow {}_7N^{16} + {}_1p^1$$

$$_0n^1 + {}_8O^{18} \longrightarrow {}_8O^{19} + \gamma$$

$$_0n^1 + {}_{27}Co^{59} \longrightarrow {}_{27}Co^{60} + \gamma$$

Tritium emits beta particles only. These cannot penetrate the walls of the moderator system piping and so would appear to be no problem. Not so. Should heavy water leak out of the moderator system, tritium is released in the form of water vapour and spreads throughout the area to become a serious airborne hazard for people breathing this air. The same is true if the system has been opened up for maintenance. Because the half-life of tritium is 12.3 years, such airborne hazards would persist for a long time if we didn't remove them with special ventilation systems. If the tritium half-life were only seconds or minutes, a lot of our problems would disappear. On the other hand, if tritium emitted gamma as well as beta, they would be much worse.

Nitrogen-16 and oxygen-19 are both beta-gamma emitters. Since the moderator circulates outside the core, through such systems as the moderator cooling and moderator purification systems, those systems will become a hazard external to the core. For example, at full power the high radiation fields in the Moderator Enclosure are almost entirely due to the N-16 and O-19 activation products in the moderator piping.

Steel has low concentrations of Co-59 added to it to make it harder. As the piping corrodes and erodes (i.e., gets worn away), some of the Co-59 is transported through the reactor core and activated to Co-60. This long-lived Co-60 (5.3 y) will be deposited on the moderator system piping, mainly outside the core, resulting in high gamma fields long after shutdown.

During reactor shutdown the formation of radioactive nuclei by activation stops. Other than Co-60, most gamma emitters in the moderator have short half-lives and quickly disappear. (The half-lives of nitrogen-16 and oxygen-19 are 7 and 27 seconds respectively.)

The Heat Transport System

The primary heat transport system circulates the coolant from the core to the boilers and back again. Since the coolant is also heavy water, the same N-16 and O-19 activation products are formed in the coolant as in the moderator. The heat transport system has a lot more plumbing than the moderator system and the water flow rate is a lot greater. This causes more corrosion products in the heat transport system than in the moderator system.

We already mentioned that cobalt-60 is formed by the activation of cobalt-59, a common material found in most steels. Co-60 is a particular pain because it tends to plate out on pipes and pumps, so that they remain radioactive hazards long after the reactor has been shut down. For this reason a considerable effort was made during construction to procure steels with as low a cobalt content as possible for use in the heat transport system at Point Lepreau. We felt that sacrificing hardness in primary pump bearings for reduced radiation fields was worthwhile.

Zr-95 from the activation of Zircaloy, and Fe-59 from the activation of steel are also important.

Finally, I want to emphasise again that any materials removed from the core are extremely radioactive because of the activation products they contain. This kind of work requires detailed and careful planning to control the radiation hazards.

SUMMARY

All nuclides are either stable or radioactive. Radioactive nuclei emit radiation in an attempt to become stable. The properties are summarised below:

Radiation	α	β	γ	*n*
Composition	*2p, 2n*	*1 e*	*electromagnetic radiation*	*1 n*
Mass (amu)	*4*	*1/1840*	*0*	*1*
Charge	*+2*	*–1*	*0*	*0*
Range in Air	*~ cm*	*~ m*	*~ 100 m*	*~ 100 m*
Ionise	*directly*	*directly*	*indirectly*	*indirectly*

Alpha and beta particles have a limited range in any material. Gamma and neutron radiation do not. For this reason, gamma absorption is described in terms of half-value layers.

The activity of a radiation source is the number of its nuclei decaying in one second. 1 becquerel (Bq) is 1 decay/second.

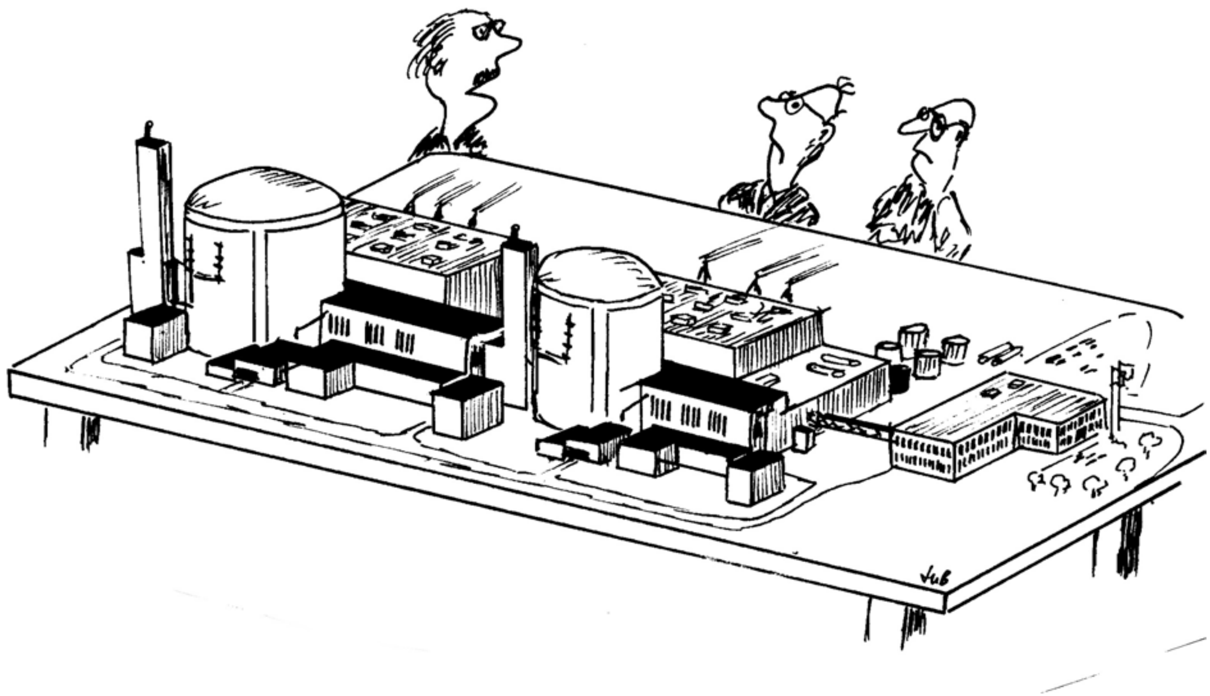
The half-life of a radionuclide is the time required for it to lose half of its activity by decay.

Fission produces neutrons, gamma rays and fission products (mostly β^-,γ *emitters). Fission products usually undergo several successive* β^-,γ *decays before they become stable.*

Photoneutrons may be produced from high-energy gamma interactions with deuterium. Neutrons produce activation products (mostly β^-,γ *emitters).*

Make sure you understand the difference between activation and contamination (page 53).

Fission products and activation products are the main sources of radioactivity in a nuclear station. After shutdown, heat transport and moderator systems are likely to contain significant radiation hazards from long-lived activation products. If there is failed fuel, radiation hazards from the heat transport system are increased due to the presence of fission products.



"There must be some misunderstanding, the 3.2 billion was just for the model"

PROBLEMS

Radioactivity

1. What is the difference between a stable nuclide and a radioactive nuclide?

2. Name three ways by which a radionuclide can become stable.

3. What do alpha particles become after they have slowed down?

4. What distinguishes gamma rays, X-rays and light waves from one another?

5. If a nuclide emits an alpha particle, what is the change in mass of the nuclide?

6. A TV set has a voltage difference of 25,000 volts between the cathode (where the electrons are emitted) and the anode (the screen they hit). What is the energy (in keV) of an electron when it hits the screen? If you increase the high voltage, what would happen to the brightness?

Ionisation

7. What is meant by the term "ions"? Why do they come in pairs?

8. What is the difference between direct ionisation and indirect ionisation?

9. State the three processes by which gamma rays interact with matter. Describe the Compton effect and the photoelectric effect in your own words.

10. Why are alpha emitters a more serious hazard than beta emitters are once they are inside the body?

Penetrating Ability

11. Assume that it takes 34 eV to produce an ion pair in air.
    (a) How far would a 1 MeV beta travel in air?
    (b) How far would a 1 MeV alpha travel in air?
    Use the information given in Fig. 2.6.

12. (a) Work out the range in air of a 2 MeV alpha particle.
    (b) Why do the 1 MeV beta particles (question 11) travel so much further when they only have half the energy?

13. Can you think of exceptions to the statement “beta particles always have a greater range in air than alpha particles”?

14. The relationship between the range of alpha particles in air and in tissue is

(range in air) x (density of air) = (range in tissue) x (density of tissue)

Calculate the range of alpha particles in tissue. Use the data of Fig. 2.12. The density of air is 1.29 kg/m^3. Take the density of tissue to be the same as that of water.

15. Why do gamma photons not have a definite range, like alpha and beta particles?

16. Yttrium-90 emits beta particles (no gamma) with a maximum energy of 2.2 MeV. If it takes 34 eV to create an ion pair in air, and if 10 ion pairs are produced per mm, calculate how far away from an unshielded Y-90 source would you have to stand to be sure that none of the beta particles could reach you? How does your answer compare with Fig.2.14?

17. Although Fig. 2.15 shows that 2 mm of lead would be sufficient to completely shield the Y-90 source, why is it not a good idea to use lead? And what sort of material should be used instead?

18. In a chemical analysis, a solution of a high-energy beta emitter (no gamma) was being evaporated to dryness in a glass beaker. A survey meter used for measuring low level gamma radiation indicated no radiation initially. As the solution evaporated, an increasing reading was obtained. Explain.

19. The concrete shielding provided by the "quadricell" structures in our Solid Radioactive Waste Management Facility (SRWMF, pronounced "Smurf") is 0.95 m thick. The HVL of this concrete for 1 MeV gamma radiation is about 50 mm. Work out by what factor the radiation is reduced in passing through this 0.95 m thickness.

20. Why is water a good material for slowing down neutrons?

Decay Schemes

21. Define "parent" and "daughter".

22. What is the mass number and atomic number of the daughter atom that results from the alpha decay of U-234?

23. $_{88}Ra^{226}$ is formed by alpha decay. What are the mass and atomic numbers of the parent nucleus?

24. In beta decay, how does the daughter nucleus differ from the parent nucleus?

25. What happens in the nucleus to produce this change?

26. Argon-41 decays by β^-,γ emission to which isotope of potassium?

27. Does $_{16}S^{31}$ decay to $_{15}P^{31}$ by β^- or β^+ emission?

28. (a) How does gamma emission differ from alpha and beta disintegration?

    (b) What effect does gamma emission have on the structure of the emitting nucleus?

29. Explain "disintegration" or "decay" series.

30. The atomic numbers and chemical symbols of a number of elements are as follows:

Uranium	U	92	Radon	Rn	86
Protactinium	Pa	91	Astatine	At	85
Thorium	Th	90	Polonium	Po	84
Actinium	Ac	89	Bismuth	Bi	83
Radium	Ra	88	Lead	Pb	82
Francium	Fr	87	Thallium	Tl	81

    The actinium decay series starts with the nuclide U-235. Successive decays α, β^-, α, β^-,α, α, α, α, β^-, β^-, and α emissions finally lead to the production of stable Pb-207. List all the intermediate nuclides produced.

Activity and Half-Life

31. Define half-life.

32. Given a radioactive substance, how much of the original material will remain after three half-lives?

33. Using Fig. 2.24, determine the number of half-lives required to reduce a radioactive source to (a) 50%, (b) 10%, (c) 1% of its original activity.

34. How much activity does 7 Bq represent? 8 MBq? 9 TBq?

35. (a) What is the half-life of Cs-137?

    (b) Given 1 milligram of Cs-137, how much Cs-137 will be left after 75 years?

    (c) How much will remain after 120 years?

    (d) Where did the missing Cs-137 go?

36. Cobalt-60 is used as a source of gamma radiation in radiotherapy machines. Co-60 has a half-life of 5.3 years. A 1 g Co-60 capsule was installed in such a machine in June 1993. What percentage of the original activity remains now?

37. Does the capsule of question 36 still weigh 1 gram or not? Explain why.

38. A source contains two radionuclides, A and B. A has a half-life of one day, and B has a half-life of one month. Initially the source has a total activity of 1000 Bq with equal contributions from A and B. What will the activity be after one day, one month, and one year?

39. A nuclear generating station has a liquid waste tank of 50 m^3 capacity. Analysis of a tank sample indicates the following concentrations:

Nuclide	Concentration	Half-Life
I-135	60 MBq/m^3	7 hours
I-131	140 MBq/m^3	8 days
Cs-137	5 MBq/m^3	30 years

If the tank is half full, how long will it take until it contains no more than 1 GBq of total activity from these three radionuclides?

40. Calculate the activity in Bq of potassium-40 in your body, assuming that 0.35% of your body weight is potassium, and 0.0117% of the potassium is K-40. Use the information given in the box on page 44. The half-life of K-40 is 1.29E9 y.

41. A carefully purified sample of uranium-238 weighs 6.7 mg and has a measured activity of 85 Bq. What is the half-life of U-238?

Neutrons

42. Why is it that neutrons can interact more easily with nuclei than protons can?

43. Name two possible sources of neutrons (excluding calibration sources) in a CANDU reactor.

44. Name five different interactions that neutrons can make with matter.

45. Write the equations for the inelastic scattering and the (n,γ) reactions of uranium-238. Both reactions can occur.

46. Write the equations for the (n,γ) reactions with argon-40, hydrogen-1, and cobalt-59.

47. Write the equations for the (n,p) reactions with oxygen-16 and helium-3.

48. Write the equations for the (n,α) reactions of boron-10 and lithium-6.

49. By referring to the atomic and physical properties of lead and water, and the types of processes that neutron and gamma radiations undergo when interacting with these two shielding materials, explain:
    (a) why water is suitable both for neutron and gamma shielding;
    (b) why lead is suitable for gamma shielding, but not for neutron shielding.

50. Explain the process by which a fast neutron slows down in the human body and list two possible indirect ionisation sources associated with neutrons in the body.

51. Which neutron reaction would be the most common inside the reactor when it is at power?

52. The number of elastic scattering collisions fission neutrons must make to reduce their energy from 2 MeV to thermal energy (0.025 eV) is given by 9.1A + 6, where A is the mass number. How many collisions are required in He-4, C-12, and U-238?
    So why is helium not used as a moderator?

Activation Products, Fission Products

53. Explain the terms "activation" and "contamination" when used in connection with radioactivity.

54. If an object were placed in or near a reactor core, would it be likely to become radioactive? Explain.

55. Name six sources of radiation in the reactor core.

56. (a) After reactor shutdown is the formation of radioactive nuclei by activation important? Explain.
    (b) Does the decay of activation products stop after reactor shutdown? Explain.

57. According to Figure 2.38, is it fair to say that radionuclides with mass numbers below 70 and above 160 won't be fission products?

58. Fill in the missing atomic and mass numbers in the following examples of U-235 fission:

$${}_0n^1 + {}_{92}U^{235} \longrightarrow Xe^{143} + {}_{38}Sr + 3n + \gamma$$

$${}_0n^1 + {}_{92}U^{235} \longrightarrow Kr^{92} + {}_{56}Ba + 2n + \gamma$$

$${}_0n^1 + {}_{92}U^{235} \longrightarrow {}_{38}Sr^{92} + 2n + \gamma + \text{what other fission fragment}$$

59. Why are fission fragments radioactive and what kind of radiation do most fission products emit?

60. (a) Which types of fission products are most likely to escape from defective fuel elements?

    (b) How do they become a hazard to people in the area?

61. What is the range of half-lives of the fission products of U-235?

62. In newly discharged spent fuel Sr-90 is a negligible fraction of the total activity in Bq. After 2 years the Sr-90 activity is 6% of the total, and after 10 years it is 24%. Explain this apparent increase in the fraction of Sr-90.

63. Name five important activation products in a CANDU reactor and state where they are most likely to be found.

64. Suppose several kilograms of moderator heavy water are accidentally spilled inside the Reactor Building. The tritium content of this heavy water is 500 GBq/kg. Stack releases of 10 TBq and 3 TBq are measured on the first and second days of the accident, but on the third and subsequent days the tritium release returns to the normal average of 400 GBq/d. Calculate the additional quantity of D_2O that was lost through the stack as a result of this incident, first expressing this quantity in kilograms and then in litres.

65. The energy produced in the fission of a U-235 nucleus is typically about 200 MeV. It is normally distributed as follows:

Kinetic energy of fission fragments	165 MeV
Kinetic energy of fission neutrons	5 MeV
Prompt fission gamma energy	5 MeV
Fission product decay energy	22 MeV

    In which parts of the reactor does this energy get absorbed?