10. RADIOACTIVITY LOGGING

10.1 Introduction

Radioactivity is used in several different types of logging tool. There are those that measure the natural radiation generated by the formation, such as the total and spectral gamma ray logs, and those that measure the response of the formation to radiation generated by the tool, such as the neutron, density and litho-density logs. This chapter will cover the total gamma ray log and the following one will examine the spectral gamma ray log.

10.2 Radioactivity Theory

Radioactivity is a fundamental property of the structure of all matter. The atoms of all elements have a *nucleus* which contains different numbers of *protons* and *neutrons*, which is surrounded by a sheath of *electrons* that are arranged in different energy levels. Each element is defined by the number of positively charged protons its nucleus contains. This is called the *atomic number Z.* Each nucleus also contains a number of neutrally charged neutrons, and the sum of the number of protons and neutrons in the nucleus is called the *atomic mass number*, *A*. There are a number of negatively charged electrons surrounding the nucleus equal to the number of protons within it, and their charge balances the positive charge of the protons. Since the mass of electrons is insignificant compared to the mass of the protons and neutrons, the atomic mass number is a measure of the mass of the atoms of each element. Although the number of protons and electrons for a given element is characteristic of that element, the number of neutrons is not. An element may have several *isotopes* which are atoms with different numbers of neutrons in their nucleus. Thus any given atom of an element will have a fixed atomic number, and a atomic mass number that depends upon which isotope it is. Most natural materials are a mixture of different isotopes.

Each isotope of each element is given a code ${}_ZX^A$, where X is the elemental code. For example, carbon has an atomic number *Z*=6, but 7 isotopes containing between 4 and 10 neutrons. These are ${}_6C^{10}$ to ${}_6C^{16}$. Carbon-12, ${}_6C^{12}$, is the most common isotope, and it is stable. Most of the other isotopes are not stable energetically, and decay to more stable elements by various processes whereby they lose energy by expelling particles or photons. Carbon-14, ${}_6C^{14}$, is one of these, and its decay process can be used to date archaeological remains.

There are five main methods whereby an unstable isotope can gain stability by losing energy. These are:

- Emission of an α particle, which is a helium nucleus ${}_2He^4$, and carries two positive charges.
- Emission of a β^- particle, which is a negatively charged high energy electron originating in the nucleus together with an anti-neutrino, $\underline{\nu}$.
- Emission of a β^+ particle, which is a positively charged high energy positron originating in the nucleus together with an neutrino, ν.
- Emission of a gamma rays, γ, which are high energy photons (electro-magnetic waves) and have no mass and carry no charge.
- Electron capture, which involves an electron being captured by the nucleus.

Under some circumstances neutrons may also be expelled from a material, but this is not a spontaneous decay.

Gamma rays are the most important in petrophysical logging because they have the highest penetration of all the radiations except neutrons. Their penetration ability means that they can be detected through several centimetres of cement casing. Alpha and beta particles have very limited penetration ability, being stopped immediately by any solid material.

Most isotopes found naturally in rocks are either stable, present in insignificant amounts, or generate insignificant amounts of radiation. There are, however, a few which are significant. These are:

- The potassium isotope ${}_{19}K^{40}$ (the stable forms are ${}_{19}K^{39}$ and ${}_{19}K^{41}$).
- The Thorium series isotopes.
- The Uranium-Radium series isotopes.

The first is a single gamma emission at a single energy (1.46 MeV). The last two are mixtures of unstable elements that generate each other in a series of radioactive emissions involving gamma radiation. Hence, there is a spectrum of energies produced over the range 0 MeV to 3 MeV. The energy spectra from the three gamma sources is shown in Fig. 10.1.

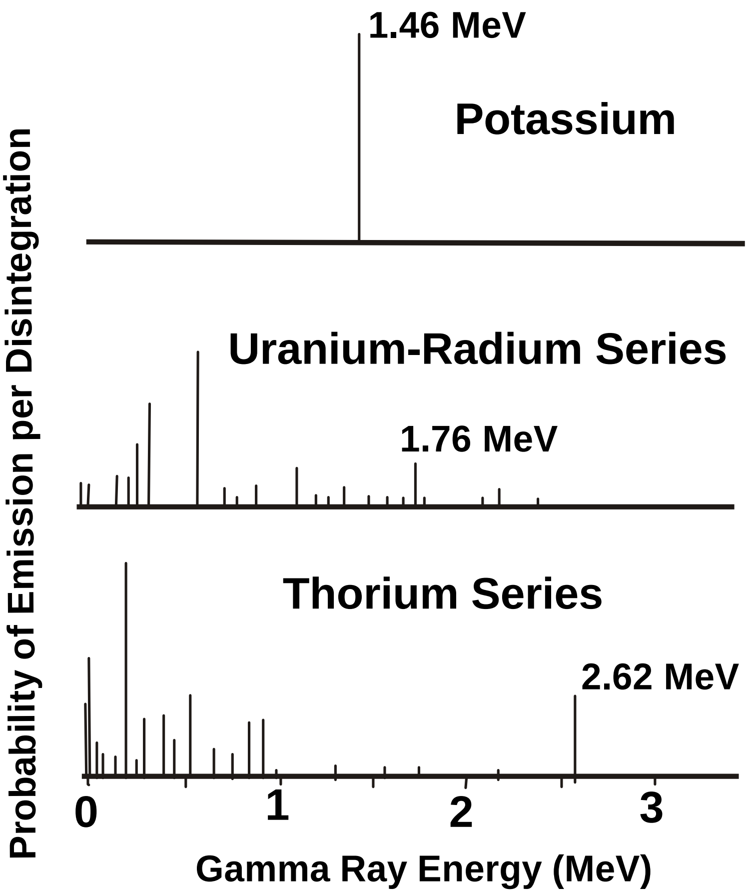

Figure 10.1 Gamma ray emission energy spectra.

The three gamma ray sources also produce different intensities of radiation per gram per second. The U-Ra series produces 26000 photons per gram per second, the Th series produces 12000 photons/g/s, and ${}_{19}K^{40}$ produces 3 photons/g/s. One might think that the potassium would be insignificant. However, the potassium is much more abundant than the isotopes in the other two series, which makes its contribution to the overall radioactivity of a formation significant. Potassium is common in most clays and some evaporites.

The most common gamma emitting lithology is shale. This is because shales are ultimately derived from igneous rocks which have significant amounts of gamma emitting isotopes. Igneous rocks are composed of quartz, feldspars and micas, the last two of which contain significant amounts of potassium and occasionally also U-Ra and Th-series isotopes. The feldspars and micas alter to clay minerals whose open lattice structure facilitates the inclusion of the larger radio-isotopes. These clays form the principle components of shales. Hence, shales can contain up to 0.3% radio-potassium and up to 0.01% of each of the U-Ra and Th-series isotopes. Unsurprisingly, potash beds are also highly radioactive.

The gamma radioactivity from minerals in petrophysical logging are measured on the API scale, described later. Table 10.1 shows typical API values for some common minerals. Note particularly that shale and some evaporites have high gamma ray values, while sandstone and limestone have low values.

Table 10.1 Gamma radiation from common minerals and lithologies (after Pirson, 1963).

Mineral or Lithology	Composition	Gamma Radiation (API Units)
Pure Mineral		
Calcite	$CaCO_3$	0
Dolomite	$CaMg(CO_3)_2$	0
Quartz	SiO_2	0
Lithology		
Limestone	-	5-10
Dolomite	-	10-20
Sandstone	-	10-30
Shale	-	80-140
Evaporites		
Halite	NaCl	0
Anhydrite	$CaSO_4$	0
Gypsum	$CaSO_4(H_2O)_2$	0
Sylvite	KCl	500
Carnalite	$KCl\ MgCl_2(H_20)_6$	220
Langbeinite	$K_2SO_4(MgSO_4)_2$	290
Polyhalite	$K_2SO_4MgSO_4(CaSO_4)_2(H_2O)_2$	200
Kainite	$MgSO_4KCl(H_2O)_3$	245
Others		
Sulphur	S	0
Lignite	$CH_{0.849}\ N_{0.015}\ O_{0.221}$	0
Anthracite	$CH_{0.358}\ N_{0.009}\ O_{0.022}$	0
Micas	-	200-350

Figure 10.2 shows the range of gamma ray values generated by common lithologies. Note the particularly high values for potash beds, which contain a large amount of potassium-40, and organic shales, which contain enhanced uranium associated with their organic nature.

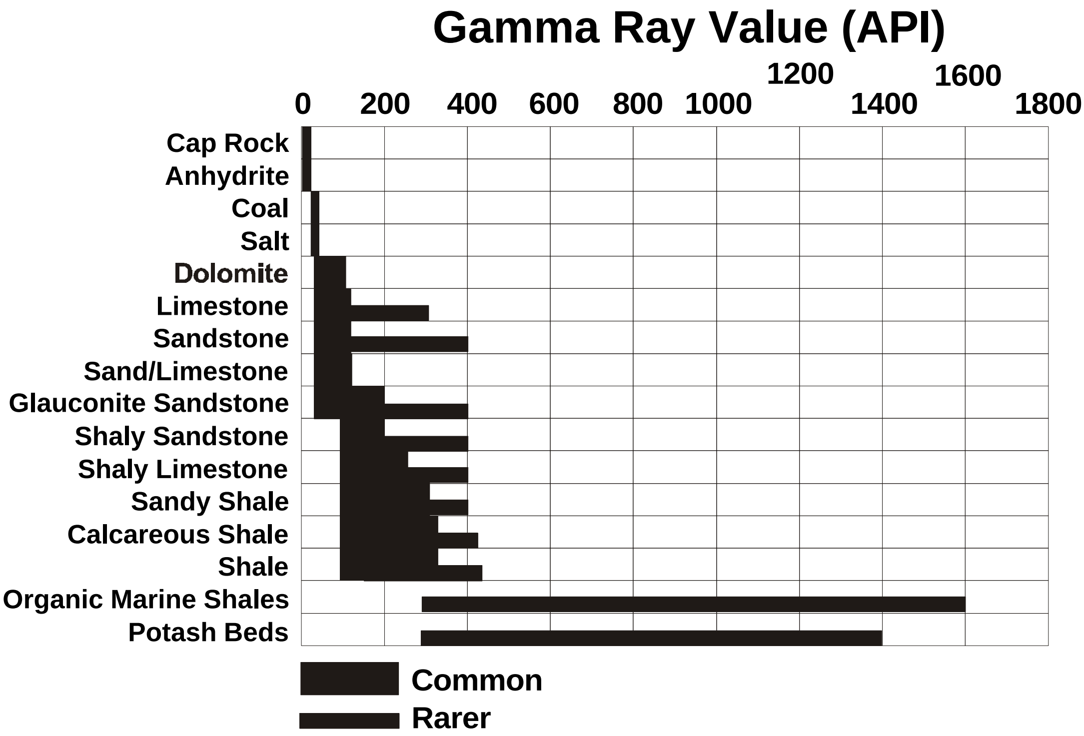

Figure 10.2 Gamma ray values from common lithologies.

10.3 Scattering and Attenuation

Once the gamma rays have been emitted they travel through materials (formation, fluids, mud cake and drilling mud) and interact with them. There are three processes that occur, and each is applicable to gamma rays with a given energy range. These are:

- **Gamma rays with energy >3 MeV.** These interact with the nucleus of the materials that they are travelling through and are converted into an electron and a positron in the process (*pair production*). The efficiency of the process is low, so these gamma rays may be measured by a sensor. However, they contribute only small amounts to the overall signal.

- **Gamma rays with energy 0.5 to 3 MeV.** These gamma rays undergo *compton scattering*, where a gamma ray interacts with the electrons of the atoms through which they are passing, ejecting the electron from the atom, and losing energy in the process. A gamma ray in this range may undergo several of these collisions reducing its energy from its initial value to an energy of less than 0.5 MeV in a stepwise fashion.

- **Gamma rays with energy <0.5 MeV.** These gamma rays collide with electrons of the atoms through which they are passing, and are adsorbed. The gamma ray energy is either used to promote the electron to a higher energy level or to eject it from the atom. This process is called *photo-electric adsorption*, and is important in the Litho-Density tool.

Thus, gamma rays start with a given energy, and are either lost through pair production, or undergo compton scattering until their energy is sufficiently low for them to be adsorbed by photo-electric absorption.

The number of collisions, hence the reduction in gamma ray energy, and the number of gamma rays adsorbed is directly related to the number of electrons in the materials through which the gamma rays pass. High count rates are observed for materials with low electron densities, and low count rates for high electron densities. The electron density is, of course, related to the mean atomic number and bulk density of the material.

Figure 10.3 shows the processes of scattering and absorption schematically.

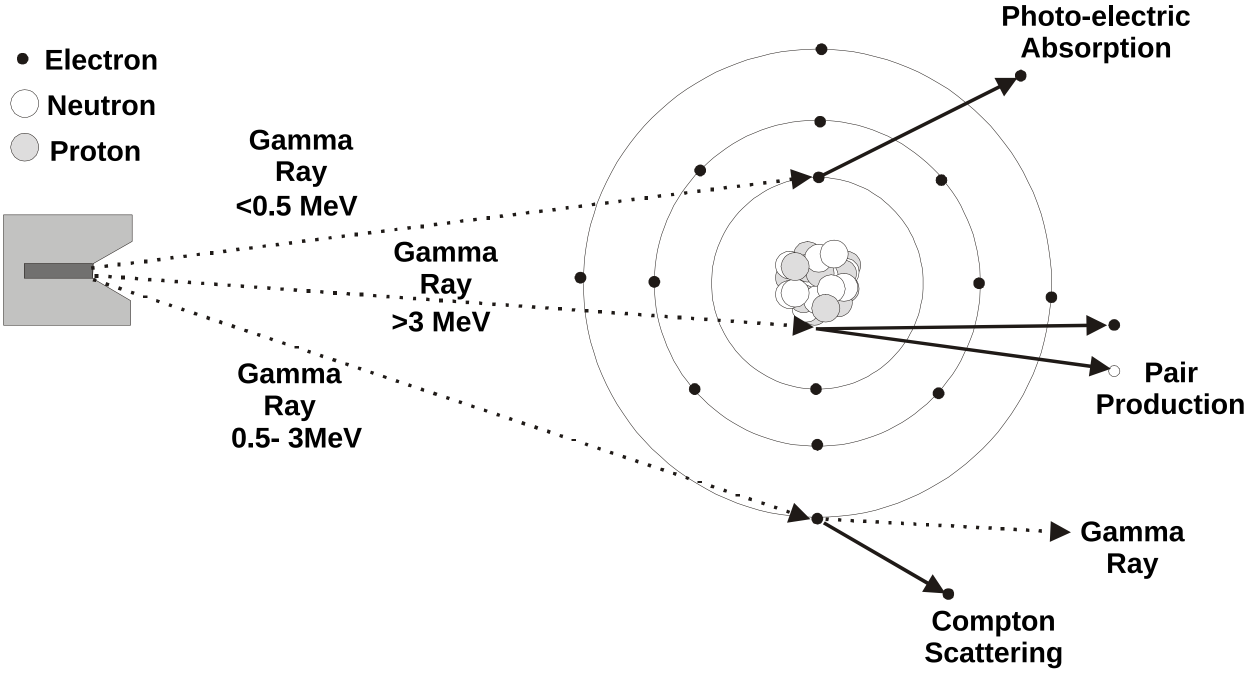

Figure 10.3 Processes of gamma ray scattering and absorption.