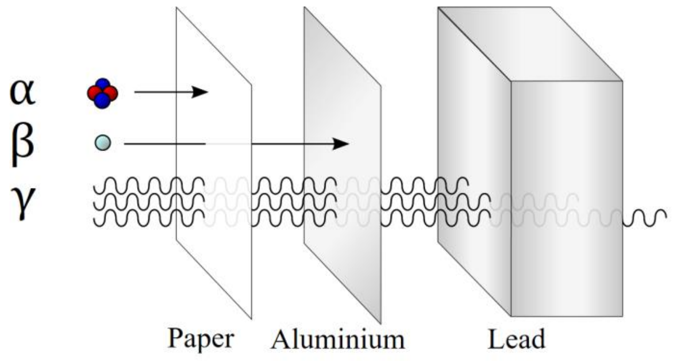
No. 3 in a series of essays on radioactivity produced by the
Royal Society of Chemistry Radiochemistry Group

Alpha, Beta and Gamma Radioactivity

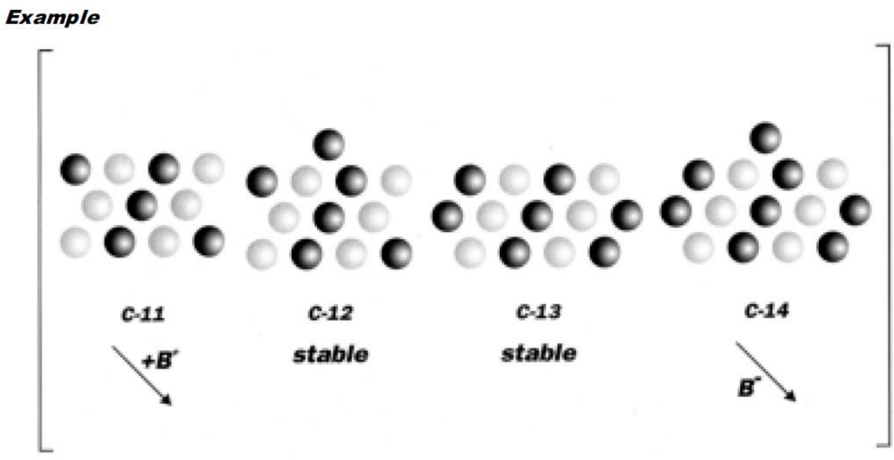


Examples of materials which will stop alpha beta and gamma radiation[1]

Unstable atoms nearly always move towards more stable configurations by emission of alpha, beta and gamma radiation.

For most elements there is a combination of neutrons and protons in the nucleus of the atom that is stable, so it has not been possible to measure any radioactive decay over extended timescales.

In some cases, there is more than one combination which gives rise to a stable atom of a given element: these have the same number of protons in the nucleus, but different numbers of neutrons. Such atoms are called isotopes.

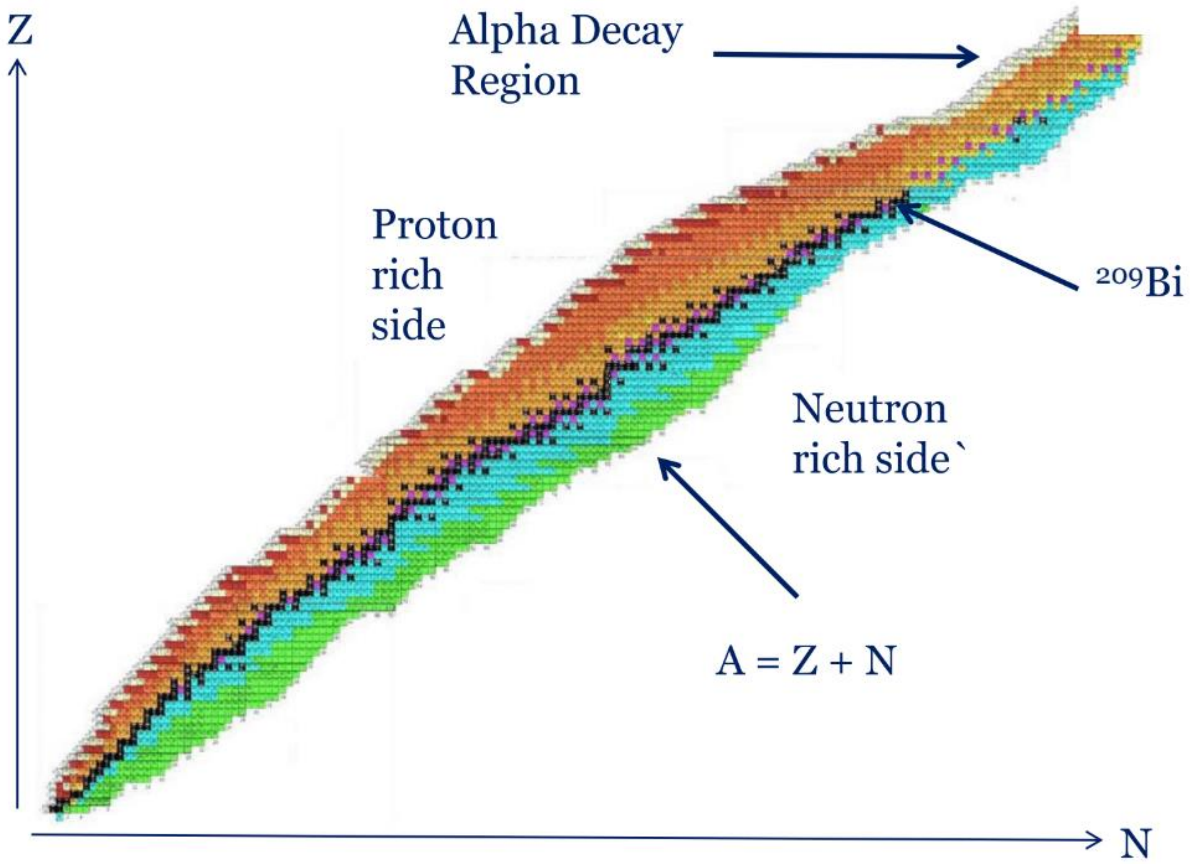


All four atoms have 6 protons which makes them carbon (or $_6C$) atoms, but they have different numbers of neutrons. Both ^{12}C and ^{13}C are stable, but ^{11}C and ^{14}C are radioactive and decay by emitting beta particles. These four are different isotopes of carbon.

In general, isotopes which have an excess of neutrons, like ^{14}C, decay by emitting negatively charged beta particles (another term for electrons).

Isotopes with a deficiency of neutrons, like ^{11}C, can decay by emitting positrons which are positively charged beta particles (electrons), or by capturing a negatively charged electron, known as electron capture.

^{11}C decays by positron emission. All elements above lead (Pb), in the Periodic Table have at least one isotope which decays by emitting alpha particles. Alpha decay is relatively rare because it requires a lot of energy to take two neutrons and two protons out of a nucleus. It is only possible in some cases because a lot of energy is gained by forming the two neutrons and two protons into an alpha particle. This gain in energy is called the binding energy.



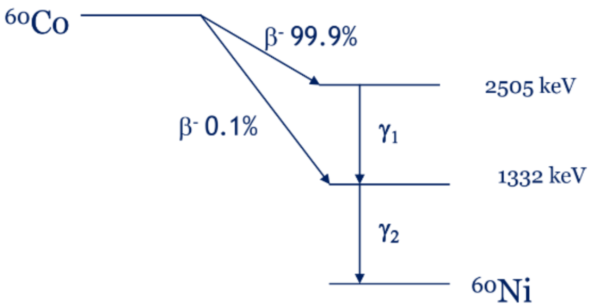
The Segrè Chart is a more complicated representation of the periodic table, listing elements and the associated isotopes (proton number, Z, on the y-axis and neutron number N on the x-axis), the black line is the so-called line of stability with the stable isotopes falling along this line. The green, blue, yellow, orange and red represent either proton or neutron rich nuclei which may decay by α, β or γ decay.[2]

γ radiation occurs when a nucleus is in an excited state. To understand this, it is useful to compare energy levels for neutrons and protons with those for electrons in an atom: Electrons occupy well-defined energy levels in an atom, and that an electron can be excited to a higher unoccupied level. This atom is then in an excited state. When the electron falls back to the lower energy level, energy is emitted from the atom in the form of electromagnetic radiation. The energy of this radiation is the difference in energy of the two levels occupied by the electron, and can be UV, visible, IR radiation or X-ray. Neutrons and protons also occupy well-defined energy levels in a nucleus, and when a neutron or a proton is excited to a higher unoccupied level the nucleus becomes excited. The excited nucleus decays to a lower energy state (the neutron or proton moves down to a lower energy level), and the difference in energy is emitted as electromagnetic radiation.

This energy difference is much larger than in the case of the electrons in atoms, (MeV, million electron volts, compared to a few eV). In the case of the nucleus the electromagnetic radiation is called gamma emission.

Alpha leading to Gamma Decay

Most isotopes that decay by α emission, do so to an excited state of the daughter nucleus; this daughter nucleus then decays to its ground state.



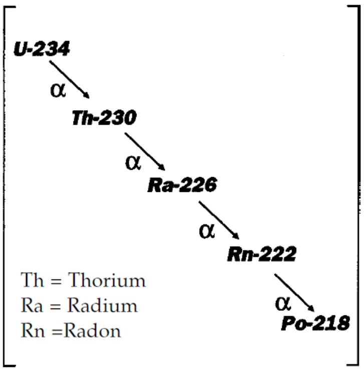
Example of ^{60}Co decay via β decay leading to two excited states which further relax to the ground state

The three different modes of decay have very different properties and are detected by different methods.

Alpha Particles

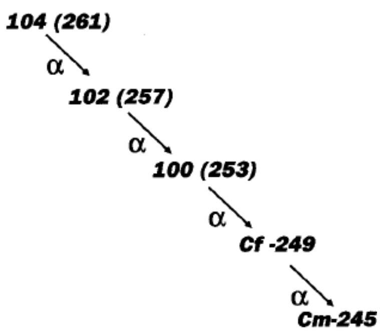
Rutherford showed that the alpha particle was the doubly charged nucleus of helium and therefore contained two protons and two neutrons.

Following α decay, the daughter nucleus has two less protons (also two less neutrons) and therefore moves two places in the Periodic Table. This can happen in a chain, a typical example is Uranium-234 (^{234}U), the decay product of ^{238}U, this decays in 4 sequential α decays to Polonium-218 (^{218}Po):



Decay scheme of ^{234}U

This phenomenon has been used to prove the identity of unknown nuclei, particularly above Z=100. An α decay chain is followed down to a known nucleus, and then the mass of the unknown isotope can be calculated. An example is element 104 of mass 261:



Decay scheme of heavy isotopes

Alpha Particles

α particles range in energy from 4 to 8 MeV and have a relatively high atomic mass of 4. For these reasons α particles travel in straight lines through matter and deposit their energy over short distances. This means that they do a lot of damage in that short distance. Their main mode of interaction is ionization, knocking electrons out of atoms. However, as Rutherford showed, in rare cases they can collide and react with the nucleus of an atom, undergoing nuclear reactions.

It is easy to protect against α particles because they can be stopped with thin materials such as paper. However, if they are ingested or get into open wounds they are very dangerous because they deposit a lot of energy in a small volume. In living tissue this results in the destruction of cells. The range of a 4 MeV α particle in air is about 2.5 cm and about 14 µm in tissue, whereas an 8 MeV alpha particle would have a range of 7 cm in air and 42 µm in tissue.

Beta Particles

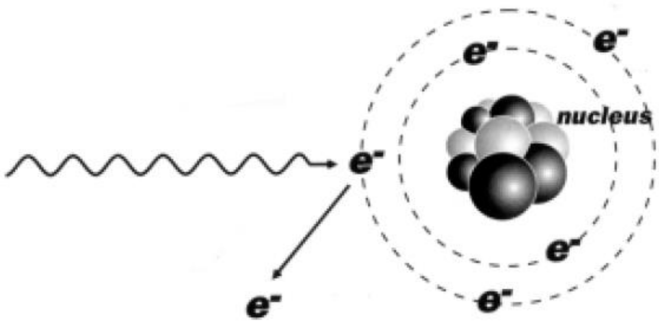
These are singly negatively charged (negatrons) or singly positively charged (positrons) electrons. They typically have energies from a few keV to a few MeV with a mass which is 1/1836 the mass of a proton. The rest masses of electrons, neutrons and protons are: 9.191×10^{-28} g, 1.675×10^{-24} g and 1.673×10^{-24} g, respectively.

From Einstein's equation: $E=mc^2$, these are equivalent to 0.511 MeV, 939.6 MeV and 938.3 MeV, respectively. The range of β particles is greater than α particles, and it requires a few mm of Al, or paper, to stop β particles of a few MeV energy. (example ^{32}P β decay of 1.7 MeV). Because they are relatively light, β particles do not travel in straight lines but follow a random path through material making it much more difficult to define a range. β particles lose energy in matter by ionization.

Gamma Rays

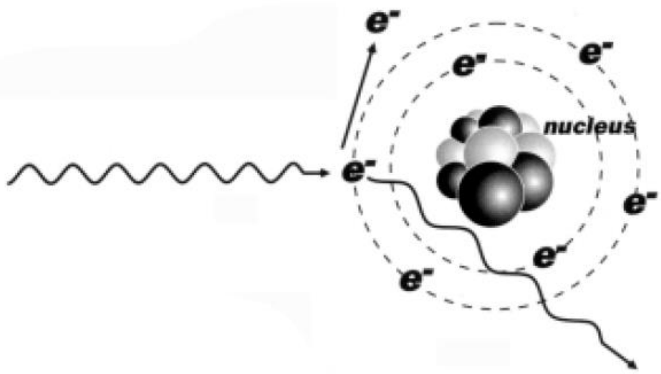
These are very short wave-length electromagnetic radiation with typical energies from 0.1 to 3 MeV in radioactive decay. Because they have no charge they have long ranges. Gamma rays lose energy by Alpha Range three major routes:

Photoelectric Effect



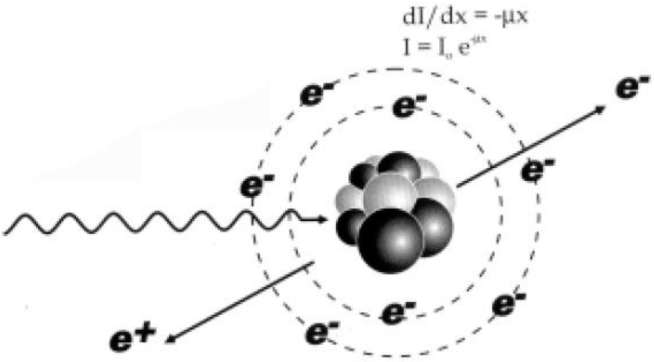
the γ ray collides with and ejects an electron from an atom losing all energy in the process, being completely absorbed.

Compton Effect



the γ ray collides with and ejects an electron from an atom and is scattered from the impact with reduced energy.

Pair Production



this involves complete absorption of the γ photon with the formation of a negatron and a positron. As we saw above, the energy of an electron is 0.511 MeV, therefore, the energy required to produce two electrons, a negatron and a positron, must be at least 1.02 MeV. This means that only γ rays with energies above 1.02 MeV can cause pair production. The produced positron annihilates with a negatron or orbital electron releasing two photons of 0.511 MeV each. These photons are then absorbed by the effects described above.

These three processes cause the γ intensity to decrease with thickness of an absorber. This decrease is directly proportional to the thickness, x. where I_0 is the intensity at the surface, I the intensity at thickness, x, and m is the absorption coefficient:

$I = I_0 e^{-mx}$

When the thickness, x = 1/ρ, where ρ is the density, the intensity is reduced to 1/e[1] (37 %) of its value at the surface of the absorber. The range for γ rays is therefore expressed in terms of a linear absorption coefficient which is the sum of the three processes mentioned above. Linear absorption coefficients (1/cm) for Al, Pb and tissue are:

	1/cm		*cm to reduce by 1/e*	
	0.5MeV	*2MeV*	*0.5MeV*	*2MeV*
Al	0.25	0.14	4.00	7.14
Pb	1.7	0.5	0.59	2.00
tissue	0.035	0.031	28.6	32.3

Range required to reduce by 1/e for example materials

Application of Alpha, Beta and Gamma Activity

There are many applications of α, β and γ radiation that support fundamental research areas and the modern world.

A few examples of these would be; sterilisation of items for use in medicine, radiotherapy to kill cancerous cells, uses of radioisotopes to trace biological and chemical processes to develop new drugs and understand complex processes. The understanding of natural systems, for example, the currents of the oceans or the development cycle of plants, to the production of new isotopes to understand fundamental physics. It is also commonly used to probe the structure and degradation of materials for space missions.

References
[1] https://commons.wikimedia.org/wiki/File:Alfa_beta_gamma_radiation_penetration.svg
[2] Interactive chart of the nuclides, http://www.nndc.bnl.gov/chart/