Radioactivity
Parents and Daughters

What is radioactivity?

Radioactivity is a collective term for a variety of spontaneous processes by which a nucleus can emit ionizing radiation in the form of a photon or a high energy particle. It is characterized by the emission of radiation which can penetrate into solid objects, and in the case of living organisms cause damage to DNA.

We shall discuss the term ionizing radiation in more depth in a later class. For the moment we shall adopt the definition that radiation is termed ionizing if the energy exceeds roughly 5 eV. This definition includes not only radiation derived from the nucleus, but also radiation from the atomic electrons (UV, X rays). For the moment we will concentrate on nuclear radiation, and return to other forms of ionizing radiation later in the course.

What causes radioactivity?

As with all physical systems a nucleus will always try to reduce its mass (equivalent to energy) by any means possible. If the nucleus can find no process which allows it to reduce the mass then the nucleus is not radioactive. Such nuclei are described as stable.

For other nuclei there is one (often more than one) process which allows the mass to decrease. In these cases the nuclei are described as unstable or radioactive. We can think of their radioactive nature as being caused by the ability to lose mass, which when converted to energy (according to Einstein's relationship) becomes the energy of the radioactive particle which is emitted.

Radioactive processes

There are a variety of processes which have the potential to decrease the mass of the nucleus

- Alpha (α) decay in which a particle comprised of two protons and two neutrons is ejected at high speed.
- Beta (β) decay in which either an electron or a positron is ejected at high speed.
- Gamma (γ) emission in which the nucleus emits a high energy photon.
- Electron capture when the nucleus captures on of the atomic electrons surrounding the nucleus.
- Internal conversion in which one of the atomic electrons is ejected from the atom without changing the nucleus.
- Relatively rare processes such as proton emission, cluster decay, and spontaneous fission.

In this class we shall focus on the first three.

Alpha decay

Alpha decay is the process by which a parent nucleus loses energy (mass) by releasing an alpha particle, which comprises two protons and two neutrons. This particle is equivalent to the nucleus of a helium atom, with two positive charges and an atomic mass of four. A brand new nucleus, known as the daughter, is left behind. Schematically

$$\text{parent} \rightarrow \text{daughter} + {}^{4}_{2}\text{He}$$

Alpha decay will proceed any time the mass of the parent nucleus is greater than the combined mass of the daughter and He nuclei. As a general rule isotopes of elements with high atomic number are unstable against alpha decay, although there are exceptions.

Determination of the identity of the daughter nucleus is straightforward. All we need to do is count the number of protons and the number of neutrons, and account for the fact that two of each leave with the alpha particle. Schematically

Isotope	Atomic Number	Atomic Mass	# of protons	# of neutrons
Parent	Z	A	Z	N (= A - Z)
Daughter	Z - 2	A - 4	Z - 2	N - 2

For example, the isotope ${}^{176}\text{Au}$ (Au = gold) is an alpha emitter. Gold has an atomic number of 79, meaning that this particular isotope of gold has a nucleus consisting of 79 protons and 97 neutrons. After two of each leave to make up the alpha particle the daughter nucleus must be left with 77 protons and 95 neutrons. The 77 protons are sufficient to identify the new element as iridium (Ir = iridium). Adding the number of protons and neutrons together gives the atomic mass of the iridium isotope, 172. We can then fill in the details for the radioactive process and write

$${}^{176}_{79}\text{Au} \rightarrow {}^{172}_{77}\text{Ir} + {}^{4}_{2}\text{He}$$

Some other examples of alpha decay are given in the table to the right. Note that in all cases the daughter nucleus has an atomic number with is two less than the atomic number of the parent, and an atomic mass which is four less than the atomic number of the parent.

${}^{196}_{84}\text{Po} \rightarrow {}^{192}_{82}\text{Pb} + {}^{4}_{2}\text{He}$

${}^{159}_{74}\text{W} \rightarrow {}^{155}_{72}\text{Hf} + {}^{4}_{2}\text{He}$

${}^{243}_{95}\text{Pu} \rightarrow {}^{239}_{93}\text{Np} + {}^{4}_{2}\text{He}$

${}^{144}_{60}\text{Nd} \rightarrow {}^{140}_{58}\text{Ce} + {}^{4}_{2}\text{He}$

${}^{252}_{99}\text{Es} \rightarrow {}^{248}_{97}\text{Bk} + {}^{4}_{2}\text{He}$

Some other examples of alpha emitters

Beta decay

A nucleus which is a beta emitter ejects either an electron (e-) or a positron[1] (e+). Since both of these particles have a very small mass, the atomic mass of the atom is unchanged. However, in the case of an electron emitter (β- decay), such as the decay of ${}^{24}\text{Na}$, the number of protons in the nucleus has to increase by one in order to conserve the total charge. Since there are 11 protons in a sodium nucleus, the daughter nucleus must have 12 protons, and so must be the nucleus of a magnesium atom

$${}^{24}_{11}\text{Na} \rightarrow {}^{24}_{12}\text{Mg} + {}^{0}_{-1}\text{e}$$

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[1] The positron is the anti particle to the electron. It has the same mass, but a positive charge instead of a negative charge.

Since the total number of nucleons (the atomic mass) remains unchanged the increase in the number of protons by one is accompanied by a decrease in the number of neutrons by one. In effect one of the original neutrons has been turned into a proton, with the emission of the electron.

In the case of a positron emitter (β+ decay) charge conservation requires the number of protons decreases by one, such as the decay of 40K

$$^{405}K \rightarrow {}^{40}_{18}Ar + {}^{0}_{+1}e$$

$^{101}_{42}Mo \rightarrow {}^{101}_{43}Tc + {}^{0}_{-1}e$

$^{30}_{13}Al \rightarrow {}^{30}_{14}Si + {}^{0}_{-1}e$

$^{39}_{18}Pu \rightarrow {}^{39}_{19}K + {}^{0}_{-1}e$

$^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{+1}e$

$^{18}_{9}F \rightarrow {}^{18}_{8}O + {}^{0}_{+1}e$

Some other examples of beta emitters

In this case a proton has been turned into a neutron, with the emission of the positron.

Gamma decay

Gamma (γ) decay is fundamentally different to alpha and beta decay in that no part of the original nucleus is ejected. There is no change in either the atomic number or the atomic mass of the nucleus, and the parent and daughter are the same. Instead the nucleus simply loses energy, and that energy appears as a photon of electromagnetic radiation, the gamma ray.

The question then remains, where does the nucleus get the extra energy from? Gamma decay usually follows an earlier beta decay. For example, ^{137}Cs is usually listed as a gamma emitter. However, ^{137}Cs is actually a beta emitter

$$^{137}_{53}Cs \rightarrow {}^{137m}_{54}Ba + {}^{0}_{-1}e$$

We can think of the barium nucleus which is formed as consisting of 137 nucleons, but arranged in a less than ideal pattern, if you like not packed as closely as they might be. When this happens the nucleus which is formed is said to be in a metastable[2] state. The nucleons will eventually rearranged themselves so that the energy of the nucleus is reduced, and the energy released becomes the gamma ray

$$^{137m}_{54}Ba \rightarrow {}^{137}_{54}Ba + {}^{0}_{0}\gamma$$

$^{60}Co \rightarrow {}^{60m}Ni + {}^{0}_{-1}e$

$^{57}Co \rightarrow {}^{57m}Ni + {}^{0}_{-1}e$

$^{22}Mg \rightarrow {}^{22m}Na + {}^{0}_{+1}e$

Some other examples of beta decay processes leading to the formation of a metastable nucleus

Radioactive series

If a parent nucleus changes by either alpha or beta decay to form a daughter nucleus, then the daughter might also be radioactive, itself a parent producing a second daughter, which might itself be radioactive, and so on. We have then a series of nuclei, each one of which produces a new daughter until the series truncates with a last daughter which is stable.

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[2] The term metastable translates as “almost stable”. The metastable nucleus is not truly stable, it will emit a gamma ray at some point, but it could be quite some time before it does so.

Since the atomic mass can only change by 0 (beta decay) or by 4 (alpha decay) four series cover all possibilities. For example, starting with ^{238}U the series can generate the atomic masses 234, 228, 224, etc.

Of these four possibilities three are found in nature, since they each contain an isotope whose half life is comparable to the age of the Earth. Each of these three is is labeled according to atomic mass of the long lived isotope, which can be considered to be the first nucleus in the series

- The 4n+2 series, corresponding to the atomic masses 238, 234, etc, and which starts with ^{238}U (half life = 4.5 billion years)
- The 4n+3 series, corresponding to the atomic masses 235, 231, etc, and which starts with ^{235}U (half life = 713 million years)
- The 4n series, corresponding to the atomic masses 232, 228, etc, and which starts with ^{232}Th (half life = 14.1 billion years)

The missing series is the 4n+1 series, corresponding to the atomic masses 241, 237, etc. The longest lived isotope in this series is ^{237}Np, with a half life of only 2.1 million years, much shorter than the age of the Earth. Even if the primitive Earth originally contained isotopes from this series they have long since decayed away. We can however synthesize this series, starting with ^{241}Pu.