RADIOACTIVE DECAY

Just as an atom can exist in any one of a number of excited states, so too can a nucleus have a set of discrete, quantized, excited nuclear states. The behavior of nuclei in transforming to more stable states is somewhat similar to atomic transformation from excited to more stable states, but there are some important differences. First, energy level spacing is much greater; second, the time an unstable nucleus spends in an excited state can range from 10^{-14} sec to 10^{11} years, whereas atomic life times are usually about 10^{-8} sec; third, excited atoms emit photons, but excited nuclei may emit photons or particles of non-zero rest mass. Nuclear reactions must obey general physical laws, conservation of momentum, mass-energy, spin, etc. and conservation of nuclear particles.

Nuclear decay takes place at a rate that follows the law of radioactive decay. Interestingly, the decay rate is dependent only on the energy state of the nuclide, it is independent of the history of the nucleus, and essentially independent of external influences such as temperature, pressure, etc. Also, it is impossible to predict when a given nucleus will decay. We can, however, predict the probability of its decay in a given time interval. The probability of decay in some infinitesimally small time interval, dt is λdt. Therefore, the rate of decay among some number, N, of nuclides is:

$$\boxed{\frac{dN}{dt} = -\lambda N} \qquad 2.1$$

The minus sign simply indicates N decreases. Equation 2.1 is a first-order rate law known as the *basic equation of radioactive decay*.

GAMMA DECAY

Gamma emission occurs when an excited nucleus decays to a more stable state. A gamma ray is simply a high-energy photon (i.e. electromagnetic radiation). Its frequency is related to the energy difference by:

$$\hbar\nu = E_u - E_l \qquad 2.2$$

where E_u and E_l are simply the energies of the upper (excited) and lower (ground) states. The nuclear reaction is written as:

$$^{A}Z^{*} \rightarrow {}^{A}Z + \gamma \qquad 2.3$$

ALPHA DECAY

An α-particle is simply a helium nucleus. Since the helium nucleus is particularly stable, it is not surprising that such a group of particles might exist within the parent nucleus before α-decay. Emission of an alpha particle decreases the mass of the nucleus by the mass of the alpha particle, and also by the kinetic energy of the alpha particle (constant for any given decay) and the remaining nucleus (because of the conservation of momentum, the remaining nucleus recoils from the decay reaction).

The escape of the α particle is a bit of a problem, because it must overcome a very substantial energy barrier, a combination of the strong force and the coulomb repulsion, to get out. For example, α particles fired at in ^{238}U with energies below 8 Mev are scattered from the nucleus. However, during α decay of ^{238}U, the α particle emerges with an energy of only about 4 Mev. This is an example of an effect called *tunnelling* and can be understood as follows. Essentially, we can never know exactly where the α particle is (or any other particle, or you or I for that matter), we only the know the probability of its being in a particular place. This probability is given by the particle's wave function, $\psi(r)$. The wave is strongly attenuated through the potential energy barrier, but there is a small but finite amplitude outside the nucleus, and hence a small but finite probability of its being located outside the nucleus.

The escape of an alpha particle leaves a daughter nucleus with mass <A-4, the missing mass is the kinetic energy of the alpha and remaining nucleus. The daughter may originally be in an excited state, from which it will decay by γ decay. Figure 2.1 shows an energy-level diagram for such a decay.

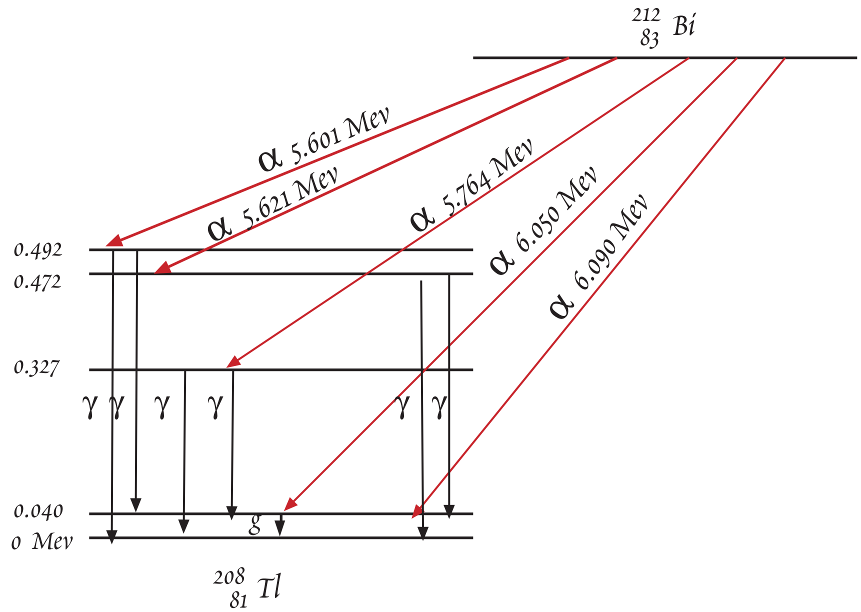

Figure 2.1. Nuclear energy-level diagram showing decay of bismuth 212 by alpha emission to the ground and excited states of thallium 208.

Alpha-decay occurs above the maximum in the binding energy curve, which occurs at ^{56}Fe. Quite possibly, all such nuclei are unstable relative to alpha-decay, but most of their half-lives are immeasurably long.

BETA DECAY

Beta decay is a process in which the charge of a nucleus changes, but the number of nucleons remains the same. If we plotted Figure 1.1 with a third dimension, namely energy of the nucleus, we would see the stability region forms an energy valley. Alpha-decay moves a nucleus down the valley axis; beta decay moves a nucleus down the walls toward the valley axis. Beta-decay results in the emission of an electron or positron, depending on which side of the valley the parent lies. Consider the 3 nuclei in Figure 2.2 (these are isobars, since they all have 12 nucleons). From what we have learned of the structure of nuclei, we can easily predict the ^{12}C nucleus is the most stable. This is the case. ^{12}B decays to ^{12}C by the creation and emission of a β^- particle and the conversion of a neutron to a proton. ^{12}N decays by emission of a β^+ and conversion of a proton to a neutron.

Here physicists had a problem. Angular momentum must be conserved in the decay of nuclei. The ^{12}C nucleus has integral spin as do ^{12}B and ^{12}N. But the beta particle has 1/2 quantum spin units. The solution was another, essentially massless particle, called the *neutrino*, with 1/2 spin to conserve angular momentum. (Whether the neutrino is actually massless or not is a BIG problem. If neutrinos have even a little mass, their collective mass could represent a significant portion of the mass of the universe; enough in fact so that the universe will eventually collapse on itself.) It is also needed to balance energy. The kinetic energies of alpha particles are discrete. Not so for betas: they show a spectrum with a characteristic maximum energy for a given decay. The neutrino also carries away part of the energy.

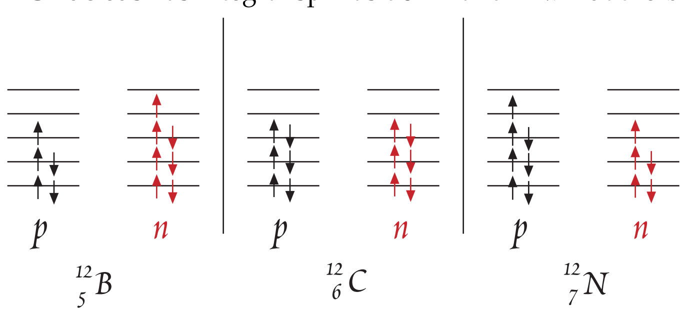

Figure 2.2. Proton and neutron occupation levels of boron 12, carbon 12 and nitrogen 12.

Beta decay involves the weak force. The weak force transforms a neutral particle into a charged one and visa versa. Both the weak and the electromagnetic force are thought to be simply a manifestation of one force that accounts for all interactions involving charge (in the same sense that electric and magnetic forces are manifestations of electromagnetism). This force is called electroweak. In β^+ decay, for example, a proton is converted to a neutron, giving up its +1 charge to a neutrino, which is converted to a positron. This process occurs through the intermediacy of the W+ particle in the same way that electromagnetic processes are intermediated by photons. The photon, pion and W particles are members of a class of particles called bosons which intermediate forces between the basic constituents of matter. However the W particles differs from photons in having a very substantial mass (almost 2 orders of magnitude greater mass than the proton). Interestingly, *Nature* rejected the paper in which Fermi proposed the theory of beta decay involving the neutrino and the weak force in 1934!

Electron Capture

Another type of reaction is electron capture. This is sort of the reverse of beta decay and has the same effect, more or less, as β^+ decay. Interestingly, this is a process in which an electron is added to a nucleus to produce a nucleus with less mass than the parent! The missing mass is carried off as energy by an escaping neutrino, and in some cases by a γ. In some cases, a nucleus can decay by either electron capture, β^-, or β^+ emission. An example is the decay of ^{40}K, which decays to ^{40}Ar by β^- and to ^{40}Ca by β^+ or electron capture.

β decay and electron capture often leaves the daughter nucleus in an excited state. In this case, it will decay to its ground state (usually very quickly) by the emission of a γ-ray. Thus γ rays often accompany β decay. A change in charge of the nucleus necessitates a rearrangement of electrons in their orbits. As electrons jump down to lower orbits to occupy the orbital freed by the captured electron, they give off electromagnetic energy. This produces x-rays from electrons in the inner orbits.

Spontaneous Fission

This is a process in which a nucleus splits into two or more fairly heavy daughter nuclei. In nature, this is a very rare process, occurring only in the heaviest nuclei, ^{238}U, ^{235}U, and ^{232}Th (it is, however, most likely in ^{238}U). It also occurs in ^{244}Pu, an extinct radionuclide (we use the term 'extinct radionuclide' to refer to nuclides that once existed in the solar system, but which have subsequently decayed away entirely). This particular phenomenon is perhaps better explained by the liquid drop model than the shell model. Recall that in the liquid drop model, there are 4 contributions to total binding energy: volume energy, surface tension, excess neutron energy, and Coulomb energy. The surface tension tends to minimize the surface area while the repulsive coulomb energy tends to increase it. We can visualize these nuclei as oscillating between various shapes. It may very rarely become so distorted by the repulsive force of 90 or so protons, that the surface tension cannot restore the shape. Surface tension is instead minimized by the splitting the nucleus entirely.

Since there is a tendency for N/Z to increase with A for stable nuclei, the parent is much richer in neutrons than the daughters produced by fission (which may range from A=30, zinc, to A=64, terbium). Thus fission generally also produces some free neutrons in addition to two nuclear fragments (the daughters). The daughters of typically of unequal size, the exact mass of the two daughters being random. The average mass ratio of the high to the low mass fragment is about 1.45. Even though some free neutrons are created, the daughters tend to be too neutron-richto be stable. As a result, they decay by β^- to stable daughters. It is this decay of the daughters that results in radioactive fallout in bombs and radioactive waste in reactors (a secondary source of radioactivity is production of unstable nuclides by capture of the neutrons released).

Some non-stable heavy nuclei and excited heavy nuclei are particularly unstable with respect to fission. An important example is ^{236}U. Imagine a material rich in U. When ^{238}U undergoes fission, some of the released neutrons are captured by ^{235}U nuclei, producing ^{236}U in an excited state. This ^{236}U then fissions producing more neutrons, etc. This is the basis of nuclear reactors and bombs (actually, most now use some other nuclei, like Pu). The concentration of U is not usually high enough in nature for this sort of thing to happen. But it apparently did once, in the Oklo U deposit in Africa. This deposit was found to have an anomalously high $^{238}U/^{235}U$ ratio (227 vs. 137.88), indicating some of the ^{235}U had been 'burned' in a nuclear chain reaction.

Individual natural fission reactions are less rare. When fission occurs, there is a fair amount of kinetic energy produced (maximum about 200 MeV), the nuclear fragments literally flying apart. These fragments damage the crystal structure through which they pass, producing 'tracks', whose visibility can be enhanced by etching. This is the basis of fission-track dating.

Natural fission also can produce variations in the isotopic abundance of elements among the natural, ultimate product. Xenon is an important product.