Section 13: Exotic Decay Modes

In addition to the principal decay modes – alpha, beta and gamma decay – there are several rare decay modes. These usually occur from nuclei far away from the line of beta stability (Fig. 2.1) or for very heavy nuclei.

One important example is **spontaneous fission (SF)**. This decay mode involves the splitting of a heavy nucleus into two intermediate-mass nuclei

$$^{A}_{Z}X \rightarrow \, ^{A_1}_{Z_1}B + \, ^{A_2}_{Z_2}C + Q_{SF},$$

where $A_1 \approx A_2 \sim A/2$ and $Z_1 \approx Z_2 \sim Z/2$. This mass and charge split is asymmetric due to the influence of nuclear closed shells at Z = 50 and N = 82, ^{132}Sn. An example is the nucleus ^{252}Cf:

$$^{252}_{98}Cf \xrightarrow{2.5y} \, ^{140}_{54}Xe^{*} + \, ^{112}_{44}Ru^{*} + Q_{SF}$$

$^{140}_{54}Xe^{*} \xrightarrow{\beta^{-},\gamma}$ STABLE $^{112}_{44}Ru^{*} \xrightarrow{\beta^{-},\gamma}$ STABLE

The primary fission products are nuclei with an excess of neutrons and subsequently undergo beta and gamma decay to stable nuclei. The above equation represents only one of many possible binary splits in fission; i.e. there is a distribution of possible fission products, giving rise to a **mass yield curve**, as shown in Fig. 13.1.

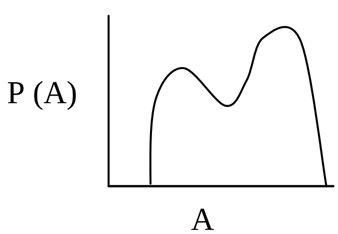


Fig. 13.1 Probability of observing a fission product of mass A as a function of A.

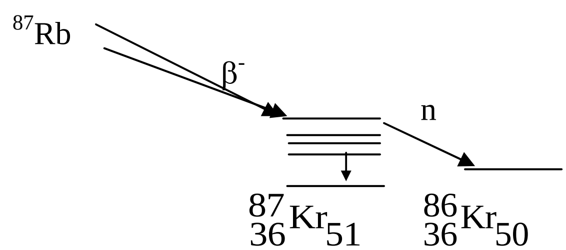
Thus, there is no specific equation that describes fission, since there are many ways the nucleus can divide, all of which increase the average binding energy of the products. The heavier of the two fission products usually is found near the doubly-closed shell Z = 50 and N = 82, indicating the strong influence of closed shells on the decay process. The lighter fragment forms the complement necessary to conserve mass and charge. This wide distribution of radioactive fission products is the major problem of nuclear waste management, as will be discussed later in the sections on nuclear reactions (Sec.15) and nuclear power (Sec. 18).

The energy release in fission is the largest of any decay mode, typically 150 – 200 MeV. For the ^{252}Cf case above, Q_{SF} is about 190 MeV. Most of this energy goes into kinetic energy of the fragments. However, the remainder (~10%) goes into heating the fragments themselves, leading to copious beta and gamma emission.

Spontaneous fission occurs only for nuclei with A > 230 and competes with the other decay modes. The lightest known SF emitter is ^{232}Th (Z=90), which has a half-life of 10^{18} years. Since SF decay is a barrier-penetration problem, it is difficult for massive nuclei to penetrate the fission barrier and therefore the probability is usually low for Z< 100. However, because of the large Z involved, there is strong Coulomb repulsion, so that the SF probability increases rapidly with increasing atomic number. For example, the nucleus ^{258}Fm (Z=100) has a spontaneous-fission half-life of only 0.4 seconds. Thus the spontaneous fission process forms a critical limitation on the synthesis of elements with Z>100 in both nature and the laboratory. Fortunately, the decay of nuclei with odd numbers of protons or neutrons is slowed down considerably, so that it is possible to extend our knowledge of the physical and chemical properties of the heaviest elements.

An exotic decay mode that is intermediate between alpha decay and spontaneous fission is **cluster** decay. Cluster nuclei such as ^{14}C, ^{18}O and ^{22}Ne have been observed in the decay of Ra, Th and U isotopes, respectively. The products are usually found near the double-closed shells Z = 82 and N = 126. The rarity of cluster emission is attributed to the high Coulomb barrier for escape from the parent nucleus and demonstrated by the fact that their probability is of the order of 10^{-10} that of competing alpha decay

Delayed proton or neutron decay is sometimes observed from highly proton- or neutron- rich nuclei. Such events usually occur from excited states following beta decay from nuclei that have been populated following a nuclear reaction. In order for delayed nucleon emission to occur, the parent nucleus must have an excitation energy in excess of the neutron or proton binding energy, $E^* > B_p$ or B_n, as illustrated below.



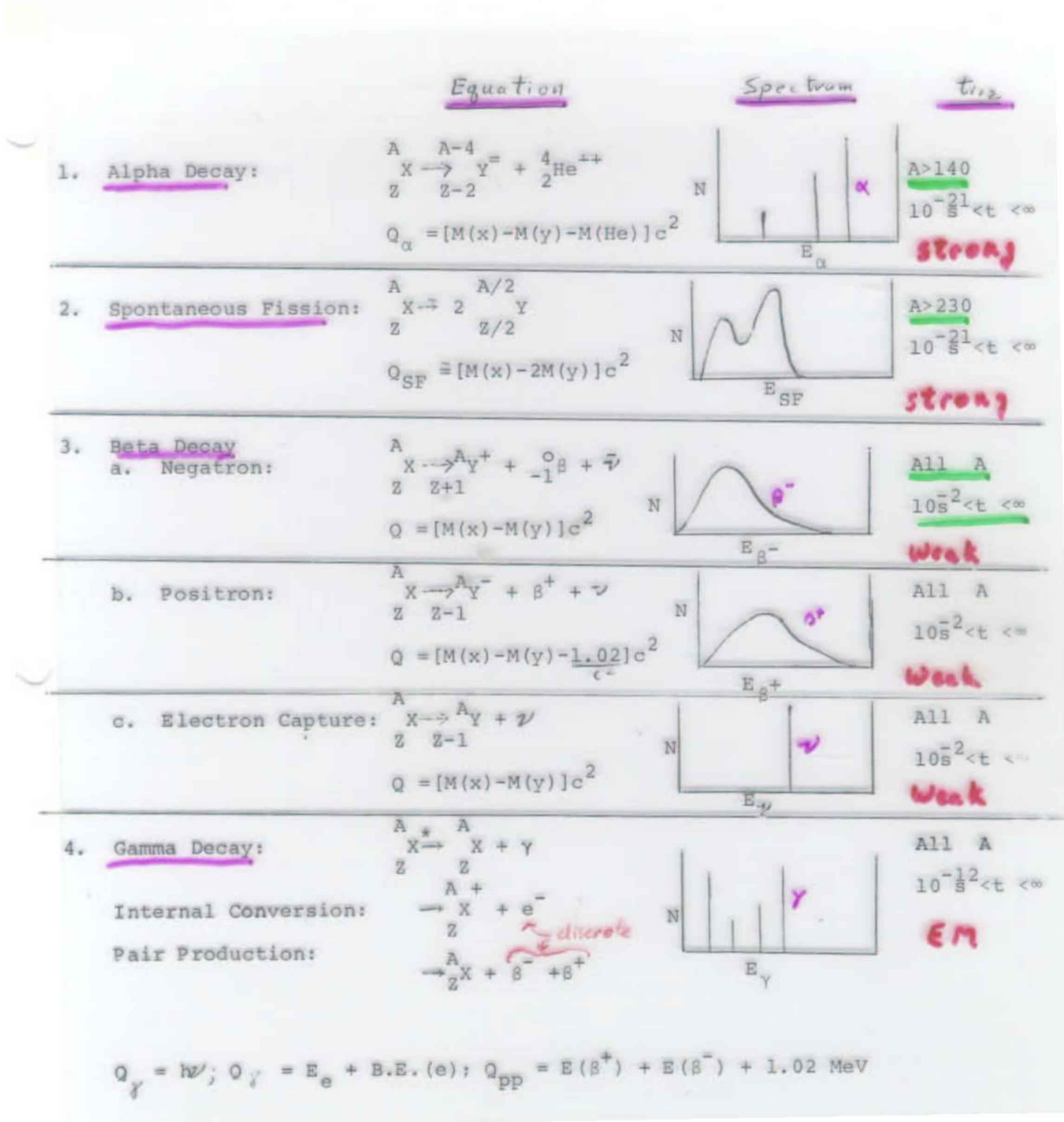
Note that the product nucleus has a closed neutron shell (N = 50), again indicating the importance of nuclear structure on the decay process.

Double beta decay is an extremely rare decay mode that incolves simultaneous emission on two negatrons and two antineutrinos

e.g. e.g. $^{130}_{52}Te \rightarrow {}^{130}_{54}Xe + 2\beta^-_{-1} + 2\,\bar{\nu} + Q_{2\beta^-}$; $Q_{2\beta^-}$

While the Q value for double beta decay is usually large (Sec. 5), the lifetime is very long, ~ 10^{21}y, due to the difficulty of producing two negatron-antineutrino pairs.

While these exotic decay modes are rare and often difficult to observe, they illustrate the multifaceted nature of radioactive decay. In all cases the eventual product is governed by the same two factors: energetics and nuclear structure. In the chart below the features of the most common radioactive decay modes are summarized.



	Equation	Spectrum	$t_{1/2}$
1. Alpha Decay:	${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y^{=} + {}^{4}_{2}He^{++}$ $Q_{\alpha} = [M(x)-M(y)-M(He)]c^2$	N, α, E_{α}	A>140 $10^{-21}s < t < \infty$ strong
2. Spontaneous Fission:	${}^{A}_{Z}X \rightarrow 2\,{}^{A/2}_{Z/2}Y$ $Q_{SF} \cong [M(x)-2M(y)]c^2$	N, E_{SF}	A>230 $10^{-21}s < t < \infty$ strong
3. Beta Decay a. Negatron:	${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{+} + {}^{0}_{-1}\beta + \bar{\nu}$ $Q = [M(x)-M(y)]c^2$	N, β^-, E_{β^-}	All A $10^{-2}s < t < \infty$ weak
b. Positron:	${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y^{-} + \beta^{+} + \nu$ $Q = [M(x)-M(y)-\frac{1.02}{c^2}]c^2$	N, β^+, E_{β^+}	All A $10^{-2}s < t < \infty$ weak
c. Electron Capture:	${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \nu$ $Q = [M(x)-M(y)]c^2$	N, ν, E_{ν}	All A $10^{-2}s < t < \infty$ weak
4. Gamma Decay: Internal Conversion: Pair Production:	${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$ $\rightarrow {}^{A}_{Z}X^{+} + e^{-}$ (discrete) $\rightarrow {}^{A}_{Z}X + \beta^{-} + \beta^{+}$	N, γ, E_{γ}	All A $10^{-12}s < t < \infty$ EM

$Q_{\gamma} = h\nu$; $Q_{\gamma} = E_e + B.E.(e)$; $Q_{pp} = E(\beta^+) + E(\beta^-) + 1.02$ MeV