1(e). Stable Nuclei

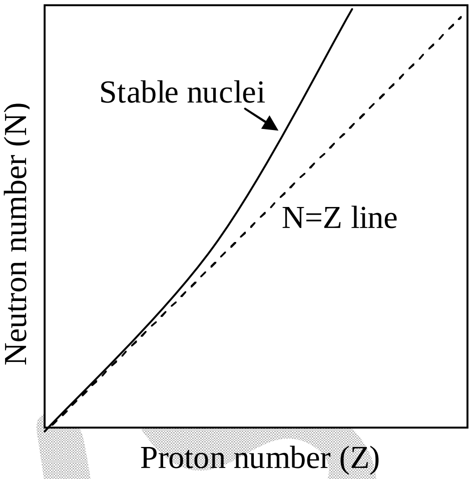

Figure: Neutron-proton diagram for stable nuclides.

Not all combination of neutrons and protons form stable nuclei. In general, light nuclei $(A < 20)$ contain equal numbers of neutrons and protons, while in heavier nuclei the proportion of neutrons becomes progressively greater. This is evident in figure as shown below, which is plot of N versus Z for stable nuclides.

The tendency for N to equal Z follows from the existence of nuclear energy levels. Nucleons, which have spin ½, obey exclusion principle. As a result, each energy level can contain two neutrons of opposite spins and two protons of opposite spins. Energy levels in nuclei are filled in sequence, just as energy levels in atoms are, to achieve configurations of minimum energy and therefore maximum stability. Thus the boron isotope ${}^{12}_{5}\mathrm{B}$ has more energy than the carbon isotope ${}^{12}_{6}\mathrm{C}$ because one of its neutrons is in a higher energy level, and ${}^{12}_{5}\mathrm{B}$ is accordingly unstable. If created in a nuclear reaction, a ${}^{12}_{5}\mathrm{B}$ nucleus changes by beta decay into a stable ${}^{12}_{6}\mathrm{C}$ nucleus in a fraction of second.

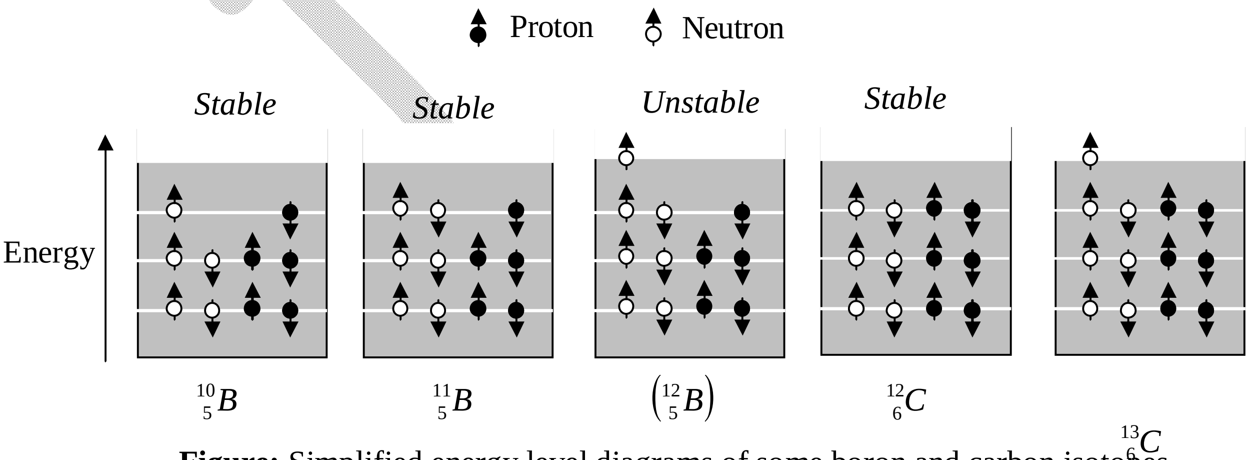

Figure: Simplified energy level diagrams of some boron and carbon isotopes.

The preceding argument is only part of the story. Protons are positively charged and repel one another electrically. This repulsion becomes so great in nuclei with more than 10 protons or so that an excess of neutrons, which produce only attractive forces is required for stability. Thus the curve departs more and more from $N = Z$ line as Z increases.

Sixty percent of stable nuclides have both even Z and even N; these are called **"even-even"** nuclides. Nearly all the others have either even Z and odd N (**"even-odd"** nuclides) or odd Z and even N (**"odd-even"** nuclides) with the numbers of both kinds being about equal. Only five stable **odd-odd** nuclides are known: ${}_1^2\mathrm{H}$, ${}_3^6\mathrm{Li}$, ${}_5^{10}\mathrm{B}$, ${}_7^{14}\mathrm{N}$ and ${}_{73}^{180}\mathrm{Ta}$. Nuclear abundances follow a similar pattern of favoring even numbers for Z and N.

These observations are consistent with the presence of nuclear energy levels that can each contain two particles of opposite spin. Nuclei with filled levels have less tendency to pick up other nucleons than those with partially filled levels and hence were less likely to participate in the nuclear reactions involved in the formation of elements.

Nuclear forces are limited in range, and as a result nucleons interact strongly only with their nearest neighbors. This effect is referred to as the **saturation** of nuclear forces. Because the coulomb repulsion of protons is appreciable throughout the entire nucleus, there is a limit to the ability of neutrons to prevent the disruption of large nucleus. This limit is represented by the bismuth isotope ${}_{83}^{209}\mathrm{Bi}$, which is the **heaviest stable** nuclide.

All nuclei with $Z > 83$ and $A > 209$ spontaneously transform themselves lighter ones through the emission of one or more alpha particles, which are ${}_2^4\mathrm{He}$ nuclei:

Alpha decay $\quad {}_Z^A\mathrm{X} \rightarrow {}_{Z-2}^{A-4}\mathrm{Y} + {}_2^4\mathrm{He}$

Since an alpha particle consists of two protons and two neutrons, an alpha decay reduces the Z and N of the original nucleus by two each. If the resulting daughter nucleus has either too small or too large a neutron/proton ratio for stability, it may beta-decay to a more appropriate configuration.

In negative beta decay, a neutron is transformed into a proton and an electron is emitted:

Negative beta decay $n^0 \to p^+ + e^-$

In positive beta decay, a proton becomes a neutron and a positron is emitted:

Positron emission $p^+ \to n^0 + e^+$

Thus negative beta decay decreases the proportion of neutrons and positive beta decay increases it. A process that competes with positron emission is the capture by a nucleus of an electron from its innermost shell. The electron is absorbed by a nuclear proton which is thereby transformed into neutron:

Electron Capture $p^+ + e^- \to n^0$

Figure below shows how alpha and beta decays enable stability to be achieved.

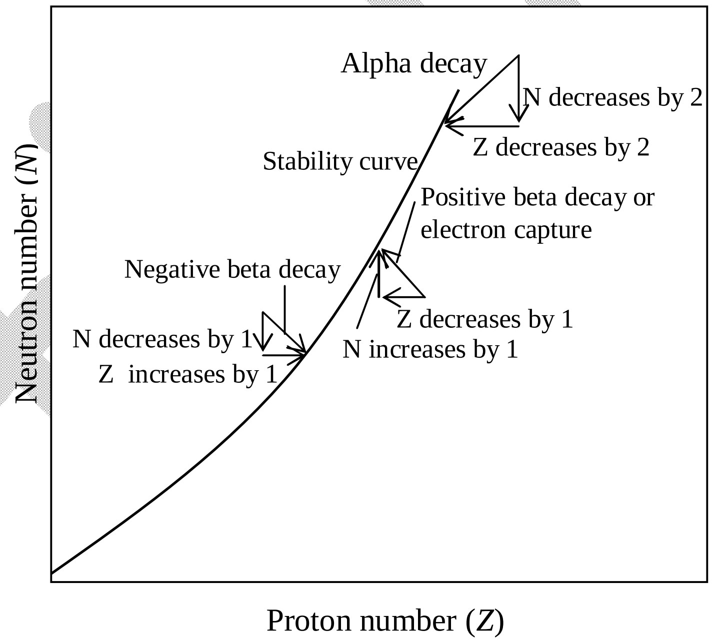

Figure: Alpha and beta decays permit an unstable nucleus to reach a stable configuration.