BISHOP HEBER
HIGH SCHOOL

Nuclear Instability

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Lesson Objectives

1. To have a basic understanding of which nuclei are likely to be stable.
2. To know the types of ‘natural’ radioactive decay.
3. To be able to write nuclear equations for these

REMINDER: Office hours are week 1 Tuesdays 3.45–5.0 p.m. in Rm. 19.
Next office hours: Tuesday 26 February 2013

Specification Requirement

Nuclear Instability
Graph of N against Z for stable nuclei.
Possible decay modes of unstable nuclei including α, β^+, β^- and electron capture.
Changes of N and Z caused by radioactive decay and representation in simple decay equations.

[AQA GCE AS and A Level Specification Physics A, 2009/10 onwards]

The discovery of radioactivity

- 1896: Becquerel noticed fogging of photographic plates left near uranium ores and not exposed to light
- Becquerel, Rutherford, Paul Villard, Pierre and Marie Curie worked out that there are various types of radiation (α and β)
- 1899: Rutherford discovered exponential decay law
- 1902: Rutherford and his student Soddy worked out that radioactivity can change one element into another
- 1903: Rutherford discovered γ rays
- 1911: Rutherford discovers the nucleus, Soddy proposes isotopes
- 1913: Fajans and Soddy worked out the decay laws for α and β
- 1932: Chadwick discovered the neutron (first predicted in 1920 by. . . ?)

Nuclide notation (revision from unit 1!)

An atom is written as

$${}^{A}_{Z}\mathrm{X}$$

where

A is the nucleon number (the number of protons and neutrons),

Z is the proton number, and

X is the element symbol.

$A - Z = N$, the neutron number.

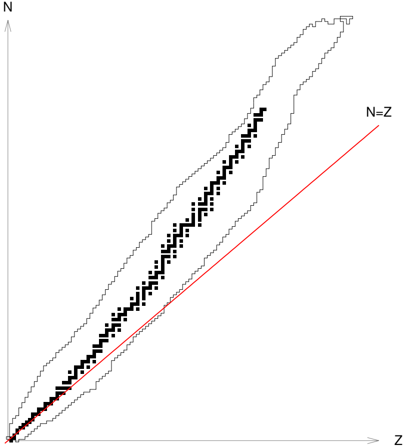
Isotopes (revision from GCSE!)

Isotopes are nuclides with the same proton number Z, but different nucleon numbers A (i.e. same number of protons, but different numbers of neutrons N).

Many elements exist in several stable isotopes, and they are not given separate names, except for:

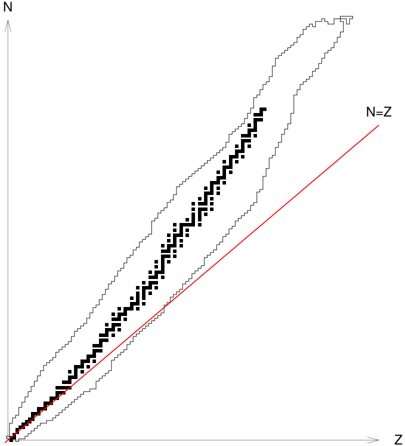
- $^{1}_{1}\mathrm{H}$ is hydrogen.
- $^{2}_{1}\mathrm{H}$ is deuterium.
- $^{3}_{1}\mathrm{H}$ is tritium.

$N - Z$ chart for stable nuclei



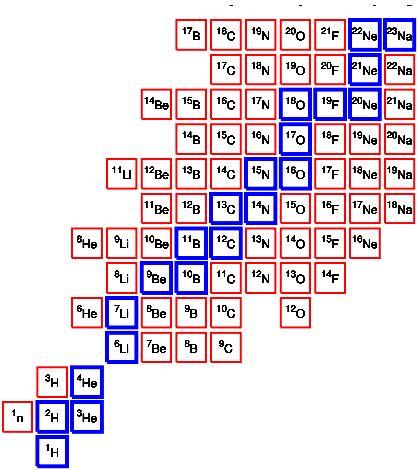
- Each black square is a stable nucleus
- The stable nuclei follow a particular curve: the *valley of stability*
- The scales on the axes step from one integer to the next (this is why it is a chart not a graph)
- The valley of stability ends at $^{209}\mathrm{Bi}$

Stable nuclei and the $N = Z$ line

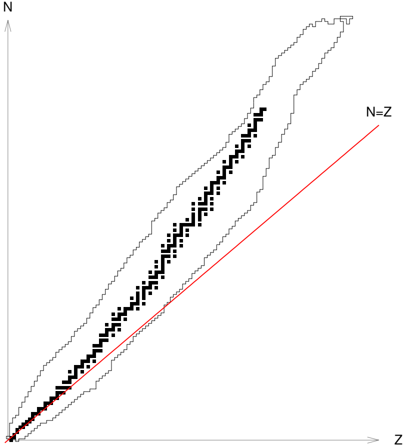


- The valley of stability coincides with the $N = Z$ line up to $Z \approx 20$
- Above this, the valley rises above the $N = Z$ line as more neutrons are needed to keep the nuclei stable
- This is because neutrons add to the strong nuclear interaction without adding to the electrostatic repulsion

Stable nuclei and the $N = Z$ line



Unstable nuclei



- Nuclei above the valley of stability are neutron-rich, and those below are proton-rich
- Unstable nuclei can reduce their energy by changing a neutron into a proton or vice versa
- The weak nuclear interaction (10^{-12} the strength of the strong interaction) allows this to occur

Radioactivity and radioactive decay

Radioactive decay:

unstable 'parent' nucleus $\longrightarrow$ more stable 'daughter' nucleus

This continues until a stable product is reached.

What might happen?

- All naturally occuring, and most artificial, radioactive are α active, or β active (or occasionally both)
- They will thus emit some combination of α, β and γ radiation
- Artificially produced unstable nuclei can do all sorts of other interesting things, but we don't need to know about this

α emission

An α particle is identical to a Helium nucleus, comprising 2 protons and 2 neutrons. This structure is very stable and tightly bound, which makes it a favourable particle to emit (as we shall see when we look at nuclear binding energy).

$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A-4}_{Z-2}\mathrm{X}' + {}^{4}_{2}\alpha$$

The energy released in α decay is carried off as kinetic energy of the outgoing particles. Many heavy nuclei with $Z > 82$ undergo α emission, leaving it closer to the stable region, e.g.

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha (4.196\,\mathrm{MeV})$$

β^- emission

A negative β particle is identical to an electron and when it is emitted, the charge on the nucleus increases by one electronic charge. A neutron has apparently changed into a proton (or, if you prefer, a down quark into an up quark), caused by the weak interaction.

$$ {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+1}\mathrm{X}' + {}^{0}_{-1}\beta^- $$

Neutron rich nuclei above the valley of stability tend to decay via β^- emission, e.g.

$$ {}^{3}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{-1}\beta^- \text{(up to 18.6 keV)} $$

Average electron energy is only about a third of 18.6 keV! (Pauli 1931)

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$$ {}^{3}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} + {}^{\;\;0}_{-1}\beta^-(\text{up to } 18.6\,\text{keV}) + \bar{\nu}(\text{up to } 18.6\,\text{keV}) $$

Average electron energy is only about a third of 18.6 keV! (Pauli 1931)

β^+ emission

A positive β particle is called a *positron* and when it is emitted, the charge on the nucleus decreases by one electronic charge. A proton has apparently changed into a neutron (or, an up quark into a down quark), caused by the weak interaction.

$$ {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{\;\;\;A}_{Z-1}\mathrm{X}' + {}^{0}_{1}\beta^{+} + \nu $$

Proton rich nuclei below the valley of stability tend to decay via β^+ emission, e.g.

$$ {}^{8}_{5}\mathrm{B} \longrightarrow {}^{8}_{4}\mathrm{Be} + {}^{0}_{1}\beta^{+}\text{(energy data?)} + \nu $$

A positron is an example of *antimatter*, predicted by Dirac several years before it was first detected by Anderson in 1932.

Electron capture

An alternative to β^+ decay for a proton rich nucleus is *electron capture*, in which a proton and one of the electrons in the atom are transformed (via the weak interaction) into a neutron and a neutrino:

$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{X}' + \nu.$$

The electron is usually captured from the innermost 'K' shell of the atom, and so this process is often called K capture. Beryllium-7 undergoes electron capture, with a half life of 53.29 days:

$$^{7}_{4}\mathrm{Be} \longrightarrow {}^{7}_{3}\mathrm{Li} + \nu$$