# NUCLEAR CHEMISTRY

## Stable and Unstable Isotopes

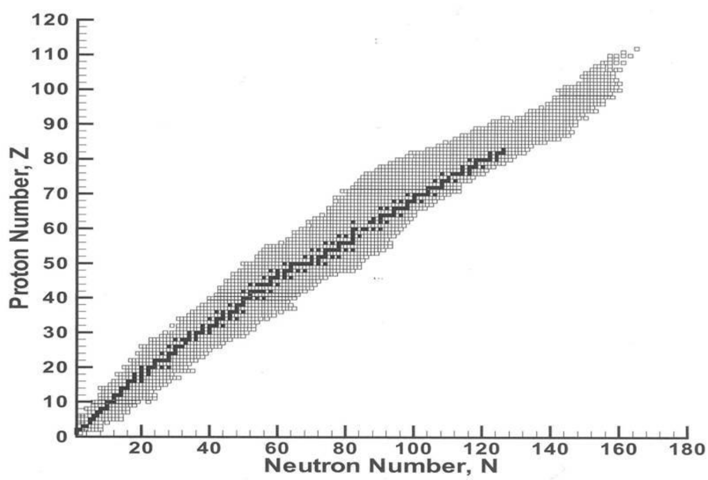
Isotopes are different forms of an element that contain the same number of protons but different numbers of neutrons, and thus their mass numbers are different.

A stable isotope is one that is not radioactive, i.e., it does not emit radiation- e.g. oxygen-16 ($^{16}_{8}O$), hydrogen-1 ($^{1}_{1}H$), carbon-12 ($^{12}_{6}C$), and lithium-6 ($^{6}_{3}Li$).

However, an unstable isotope is one that does emit radiation- in an attempt to regain stability. Unstable isotopes are also known as radioisotopes. Over time, they decay into different elements, and emit alpha ($\alpha$), beta ($\beta$), and/or gamma radiation ($\gamma$). Some naturally occurring isotopes include radium-226 ($^{226}_{88}Ra$), thorium-228 ($^{228}_{90}Th$), and uranium ($^{238}_{92}U$). However most radioisotopes are artificially produced - e.g., neptunium-239 ($^{239}_{93}Np$), plutonium-239 ($^{239}_{94}Pu$), americium-241 ($^{241}_{95}Am$) and fluorine-18 ($^{18}_{9}F$). There are no stable isotopes with atomic numbers that are greater than 83.

Isotopes are unstable due to the ratio of neutrons and protons in the nucleus-

Graph 1- those elements in black are stable, those outside this zone are unstable.




- If there are too many neutrons compared to protons in the nucleus, the neutron becomes a proton and an electron ($\beta^-$), e.g. the decay of cobalt-60 → emits beta ($\beta^-$) radiation

$$^{1}_{0}n \rightarrow \, ^{1}_{1}p + \, ^{0}_{-1}e$$

- If there are too many protons compared to neutrons in the nucleus, the proton becomes a neutron and a positron ($\beta^+$), e.g. the decay of sodium-22

$$^{1}_{1}p \rightarrow \, ^{1}_{0}n + \, ^{0}_{1}e$$

- If there are too many protons and neutrons in the nucleus (the nucleus is too heavy), the nucleus regains stability by emitting two protons and two neutrons (a helium nucleus $^{4}_{2}He$), e.g. the decay of radon-222 → emits alpha ($\alpha$) radiation

When the nucleus of a radioactive element emits radiation, a new element is often formed.

## Transuranic Elements

Transuranic elements do not occur naturally- there are artificial, made by humans. They include all elements with an atomic number over 92 (i.e., an atomic number larger than uranium), and thus, are all radioactive. An example of a transuranic element is americium ($^{241}_{95}\mathrm{Am}$). Americium is derived from plutonium ($^{239}_{94}\mathrm{Pu}$), and plutonium is derived from uranium-238 ($^{238}_{92}\mathrm{U}$).

Firstly, uranium-239 is bombarded with neutrons to form uranium-239 which then undergoes beta decay to form neptunium-239. This process occurs in a nuclear reactor.

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e}$$

Like uranium-239, neptunium -239 is a radioisotope, and thus also undergoes beta decay to form the more stable plutonium-239.

$$^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\mathrm{e}$$

Americium-241 is produced when plutonium-239 is bombarded with neutrons within a nuclear reactor-

$$^{239}_{94}\mathrm{Pu} + 2\,{}^{1}_{0}\mathrm{n} \rightarrow {}^{241}_{94}\mathrm{Pu} \rightarrow {}^{241}_{95}\mathrm{Am} + {}^{0}_{-1}\mathrm{e}$$

Figure 1- Americium-241 is used in smoke alarms

Americium-241 is used in smoke alarms. Like uranium-239 and neptunium-239, it is a radioisotope, and also undergoes beta decay, releasing electrons. These electrons ionise the surrounding air, forming an electric current in the smoke alarm, and when this current is disturbed/obstructed by smoke (e.g., from a house fire), the alarm is triggered.

Most recently, scientists have been able to produce transuranic elements by using linear accelerators and cyclotrons.

## Commercial Radioisotope (OPAL reactor, Lucas Heights)

An example of a commercial radioisotope that is produced in the Open Pool Lightwater Australian Reactor (OPAL) is silicon-31. Naturally occurring silicon-30 ($^{30}_{14}\mathrm{Si}$) is an insulator – it does not conduct electricity. However, as silicon is used by computer and electronics manufacturers in their circuits, it must undergo a process known as Neutron Transmutation Doping (NTD). In this process, silicon-30 is exposed to neutron radiation inside the OPAL reactor and is converted to silicon-31.

$$^{30}_{14}\mathrm{Si} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{31}_{14}\mathrm{Si}$$

Silicon-31 is a radioisotope, and thus undergoes radioactive decay into phosphorus-31, a stable isotope and conductor of electricity. By introducing phosphorus-31 into the silicon block, the block becomes a semi conductor, and is able to be used by computer and electronics manufacturers.

$$^{31}_{14}\mathrm{Si} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{31}_{15}\mathrm{P}$$

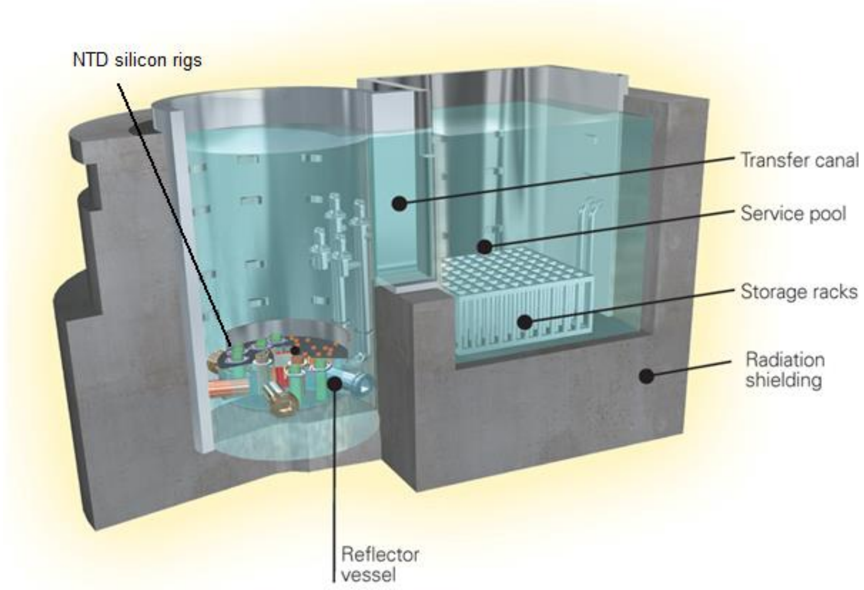



Figure 2- the OPAL reactor at Lucas Heights

In the OPAL reactor, ingots of silicon-31 are lowered from the Operation Bridge (above the Reactor Pool) into one of six irradiation rigs, in a vertical position. These ingots are exposed to nuclear radiation- they are bombarded with neutrons- and one silicon-30 atom in a billion is changed to silicon-31, which quickly decays into phosphorus-31, a conductor of electricity. The silicon ingots are also rotated whilst in the rig to ensure that the nuclear radiation is evenly distributed. After irradiation, the ingots are transferred to the Service Pool and then to the NTD Processing Laboratory by a service lift in the building.

Figure 3- A silicon ingot

Thus, by producing silicon-31, the silicon ingot is now able to conduct electricity. The final product is a semiconductor block of silicon and phosphorus which is then sliced into chips, ready to be used in the "the power transmission, manufacturing, automotive, transport, military and space industries and in scientific research."[1]

Neutron Transmutation Doping (NTD) is a more effective way of 'adding' phosphorus to large blocks of silicon, as it results in a more even distribution. The OPAL reactor at Lucas Heights is now responsible for producing 15% of the world's supply of silicon chips.

**Medical Radioisotope: Fluorine- 18 and PET**

A radioisotope used in medicine is fluorine-18 ($^{18}_{9}F$). Fluorine-18 is a radioisotope commonly used as a positron emitter to diagnose or detect diseases in a process called Positron Emission Tomography (PET).

Fluorine-18 is produced when 'enriched water' is bombarded with protons in a cyclotron. Enriched water contains oxygen-18, a naturally occurring isotope.

$$H_2\ ^{18}_{8}O + ^{1}_{1}p \rightarrow ^{18}_{9}F + ^{1}_{0}n$$

Fluorine-18 is then combined with glucose to form a radiopharmaceutical called fluorodeoxyglucose (FDG), which is then injected into or ingested by the patient prior to the PET scan. Glucose is a

[1] Open Pool Australian Light-water Reactor- www.ansto.gov.au/__data/assets/pdf_file/.../OPAL_brochure.pdf

target chemical, and is delivered to specific parts of the body- specifically those that use high amounts of glucose, e.g. the brain and malignant cells. In this way doctors are able to get the radioisotopes to a certain part of the body by combining them with the target chemical (glucose).

After ingestion, the glucose is absorbed by the body and the fluorine-18 accumulates in the targeted organ. As fluorine-18 is a radioisotope, it emits radiation when undergoing decay- namely in the form of a 'positron'.

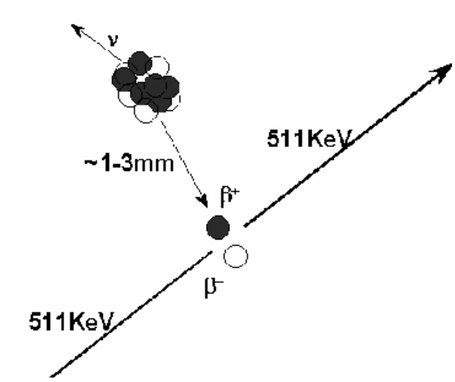



Figure 4- The annihilation of the positron results in the production of two gamma rays

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

This positron travels a range of a few millimetres in the body before meeting an electron and is annihilated, producing two gamma rays that travel nearly 180º in opposite directions. Each ray has the energy of 511 KeV.

These gamma rays are then detected by a gamma camera (also known as PET camera), and this information is fed back to a computer which then constructs a three dimensional image using this information.

### Properties That Make Fluorine-18 Suitable for PET

- Since the emitted positron does not travel far before being annihilated, the images produced have a high spatial resolution, i.e. are clearer
- Non-invasive- allows patients to have a degree of privacy
- Its half-life is only 110 minutes, thus the patient does not remain radioactive for long, and does not have to be kept in isolation for long.

Figure 5- A PET scanner

### Industrial Radioisotope: Cobalt-60 and Gamma Irradiation

Cobalt-60 (${}^{60}_{27}Co$), a radioisotope, is used in industry as a gamma irradiator to kill unwanted bacteria and microorganisms. It is used to:

- Sterilise medical equipment & supplies, so that they are safe to use
- Destroy germs and bacteria in human bone and tissue transplants, and thus DNA so that the transplants will not be rejected by the recipient's immune system. Also, to ensure that the transplants are not carrying any infections.
- Kill bacteria in food, to extend shelf life and in imported fresh fruits, it kills harmful insects and microorganisms
- To control the population of fruit flies in fruit growing regions, by sterilising fruit flies so that they cannot reproduce. When these sterilised fruit flies are released into the targeted population and mate with the local fruit flies, no offspring will be produced and thus the population is reduced

Figure 6- Universal Food Irradiation Symbol- indicates food has been through gamma irradiation

- Sterilise quarantined items from overseas, including samples for research, e.g. soil samples and ice samples from and Antarctica.

Cobalt-60 is used in gamma irradiation because it emits gamma rays ($\gamma$) when it undergoes radioactive decay.

$$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + ^{0}_{-1}e + 2\gamma$$

Gamma rays are a type of high energy electromagnetic radiation and when they come into contact with the product, this energy disturbs the electrons in the material and causes them to be highly active. In living material, this may result in damage to the DNA of cellular structures, inhibiting replication or causing death and thus the material is sterilised.

Gamma irradiation is useful because it is able to effectively sterilise products that would otherwise be destroyed by heat sterilisation. Also, it is able to easily penetrate plastic and paper, and thus the products can be packaged before irradiation. The product does not stay radioactive after gamma irradiation, and is safe to be used.


Figure 7- GATRI's Cobalt-60 Radioactive Source

Also, cobalt-60 is used for gamma irradiation because the energy it produces during radioactive decays is not strong enough to cause the exposed material to become radioactive, irrespective of the length of the dose. Cobalt-60 has a half-life of 5.3 years and thus it does not need to be replaced often and has a longer lifetime.

In Australia, gamma irradiation occurs in ANSTO's Gamma Technology Research Irradiator (GATRI) in Lucas Heights.

The products are placed in a room shielded by at least a metre of concrete. The cobalt-60 is stored in an underground pool of water. The process of gamma irradiation takes place when the cobalt-60 is raised out of the pool and the products are exposed to gamma radiation. The process can last for minutes or hours, depending on the dose required, and is controlled by an operator outside of the room.

**Hassium**


Hassium was discovered in 1984 by two German scientists, Peter Armbruster and Gottfried Munzenburg in Darmstadt, Germany. It was named 'hassium' after its place of discovery- Darmstadt is located in the German state of Hessen (Hasse in Latin). It is a transuranic element and can only be produced synthetically.

Hassium was discovered when Armbruster and Munzenburg bombarded the lead isotope, Pb-208, with iron isotopes (Fe-58) to produce about four atoms of the isotope Hs-265 with a half life of about 2 milliseconds. This occurred in a linear accelerator- which is device that accelerates particles down a long straight track and collides them with a target.

$$^{208}_{82}\mathrm{Pb} + ^{58}_{26}\mathrm{Fe} \rightarrow ^{265}_{108}\mathrm{Hs} + ^{1}_{0}\mathrm{n}$$

The properties of hassium are not well known as the isotopes produced so far have had very short half lives. Scientists do not yet know the electronegativity, melting point, boiling point, or atomic radius of this element.

However, scientists have still been able to confirm that hassium-

- Has 108 protons (atomic number)
- Is the heaviest of Group 8 elements, and is located in Period 7 of the periodic table.
- Is radioactive and extremely unstable
- Is a transition metal
- Forms an oxide when reacting with oxygen, and this oxide is able to react with sodium hydroxide
- Undergoes radioactive decay to become seaborgium

From observing the periodic table, scientists expect that hassium will have chemical properties similar to those of ossium. It is also expected that hassium will be silvery white in colour. Since hassium has a half life of two milliseconds, it currently has no real industrial, commercial or medical uses except for scientific research.

Table 1 – Different isotopes of hassium that have been produced

| **Nuclide** | **Atomic Mass** | **Number of Neutrons** | **Half Life** | **Decay Mode** | **Decays To** | **Decay Energy (MeV)** |
|---|---|---|---|---|---|---|
| Hs263 | 263.129 | 155 | <1s | α | Sg259 | |
| Hs264 | 264.128 | 156 | ~0.85ms | SF | | 10.8 |
| | | | ~0.85ms | α | Sg260 | 10.8 |
| Hs265 | 265.13 | 157 | 0.9ms | α | Sg261 | 10.82 |
| | | | 0.9ms | SF | | 10.82 |
| Hs266 | 266.13 | 158 | | | | |
| Hs267 | 267.132 | 159 | 26ms | α | | |
| Hs268 | 268.132 | 160 | | | | |
| Hs269 | 269.134 | 161 | 9s | α | | |
| α = Alpha emission<br>SF = Spontaneous Fission | | | | | | |

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