

20.3: Nuclear Transformations

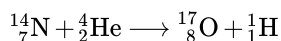
Learning Objectives

- Describe the synthesis of transuranium nuclides

After the discovery of radioactivity, the field of nuclear chemistry was created and developed rapidly during the early twentieth century. A slew of new discoveries in the 1930s and 1940s, along with World War II, combined to usher in the Nuclear Age in the mid-twentieth century. Science learned how to create new substances, and certain isotopes of certain elements were found to possess the capacity to produce unprecedented amounts of energy, with the potential to cause tremendous damage during war, as well as produce enormous amounts of power for society's needs during peace.

Synthesis of Nuclides

Nuclear transmutation is the conversion of one nuclide into another. It can occur by the radioactive decay of a nucleus, or the reaction of a nucleus with another particle. The first manmade nucleus was produced in Ernest Rutherford's laboratory in 1919 by a transmutation reaction, the bombardment of one type of nuclei with other nuclei or with neutrons. Rutherford bombarded nitrogen atoms with high-speed α particles from a natural radioactive isotope of radium and observed protons resulting from the reaction:



The ${}^{17}_8\text{O}$ and ${}^1_1\text{H}$ nuclei that are produced are stable, so no further (nuclear) changes occur.

To reach the kinetic energies necessary to produce transmutation reactions, devices called **particle accelerators** are used. These devices use magnetic and electric fields to increase the speeds of nuclear particles. In all accelerators, the particles move in a vacuum to avoid collisions with gas molecules. When neutrons are required for transmutation reactions, they are usually obtained from radioactive decay reactions or from various nuclear reactions occurring in nuclear reactors.

CERN Particle Accelerator

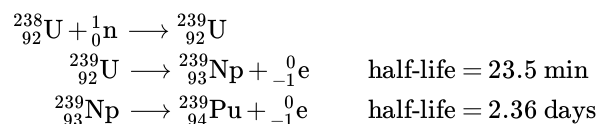
Located near Geneva, the CERN ("Conseil Européen pour la Recherche Nucléaire," or European Council for Nuclear Research) Laboratory is the world's premier center for the investigations of the fundamental particles that make up matter. It contains the 27-kilometer (17 mile) long, circular Large Hadron Collider (LHC), the largest particle accelerator in the world (Figure 20.3.1). In the LHC, particles are boosted to high energies and are then made to collide with each other or with stationary targets at nearly the speed of light. Superconducting electromagnets are used to produce a strong magnetic field that guides the particles around the ring. Specialized, purpose-built detectors observe and record the results of these collisions, which are then analyzed by CERN scientists using powerful computers.



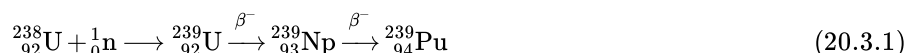
Figure 20.3.1: A small section of the LHC is shown with workers traveling along it. (credit: Christophe Delaere)

In 2012, CERN announced that experiments at the LHC showed the first observations of the Higgs boson, an elementary particle that helps explain the origin of mass in fundamental particles. This long-anticipated discovery made worldwide news and resulted in the awarding of the 2103 Nobel Prize in Physics to François Englert and Peter Higgs, who had predicted the existence of this particle almost 50 years previously.

Prior to 1940, the heaviest-known element was uranium, whose atomic number is 92. Now, many artificial elements have been synthesized and isolated, including several on such a large scale that they have had a profound effect on society. One of these—element 93, neptunium (Np)—was first made in 1940 by McMillan and Abelson by bombarding uranium-238 with neutrons. The reaction creates unstable uranium-239, with a half-life of 23.5 minutes, which then decays into neptunium-239. Neptunium-239 is also radioactive, with a half-life of 2.36 days, and it decays into plutonium-239. The nuclear reactions are:



Plutonium is now mostly formed in nuclear reactors as a byproduct during the decay of uranium. Some of the neutrons that are released during U-235 decay combine with U-238 nuclei to form uranium-239; this undergoes β decay to form neptunium-239, which in turn undergoes β decay to form plutonium-239 as illustrated in the preceding three equations. It is possible to summarize these equations as:



Heavier isotopes of plutonium—Pu-240, Pu-241, and Pu-242—are also produced when lighter plutonium nuclei capture neutrons. Some of this highly radioactive plutonium is used to produce military weapons, and the rest presents a serious storage problem because they have half-lives from thousands to hundreds of thousands of years.

Although they have not been prepared in the same quantity as plutonium, many other synthetic nuclei have been produced. Nuclear medicine has developed from the ability to convert atoms of one type into other types of atoms. Radioactive isotopes of several dozen elements are currently used for medical applications. The radiation produced by their decay is used to image or treat various organs or portions of the body, among other uses.

The elements beyond element 92 (uranium) are called transuranium elements. As of this writing, 22 transuranium elements have been produced and officially recognized by IUPAC; several other elements have formation claims that are waiting for approval. Some of these elements are shown in Table 20.3.1.

Table 20.3.1: Preparation of Some of the Transuranium Elements

Name	Symbol	Atomic Number	Reaction
americium	Am	95	${}_{94}^{239}\text{Pu} + {}_0^1\text{n} \longrightarrow {}_{95}^{240}\text{Am} + {}_{-1}^0\text{e}$
curium	Cm	96	${}_{94}^{239}\text{Pu} + {}_2^4\text{He} \longrightarrow {}_{96}^{242}\text{Cm} + {}_0^1\text{n}$
californium	Cf	98	${}_{96}^{242}\text{Cm} + {}_2^4\text{He} \longrightarrow {}_{98}^{243}\text{Bk} + 2{}_0^1\text{n}$
einsteinium	Es	99	${}_{92}^{238}\text{U} + 15{}_0^1\text{n} \longrightarrow {}_{99}^{253}\text{Es} + 7{}_{-1}^0\text{e}$
mendelevium	Md	101	${}_{99}^{253}\text{Es} + {}_2^4\text{He} \longrightarrow {}_{101}^{256}\text{Md} + {}_0^1\text{n}$
nobelium	No	102	${}_{96}^{246}\text{Cm} + {}_6^{12}\text{C} \longrightarrow {}_{102}^{254}\text{No} + 4{}_0^1\text{n}$
rutherfordium	Rf	104	${}_{98}^{249}\text{Cf} + {}_6^{12}\text{C} \longrightarrow {}_{104}^{257}\text{Rf} + 4{}_0^1\text{n}$
seaborgium	Sg	106	${}_{82}^{206}\text{Pb} + {}_{24}^{54}\text{Cr} \longrightarrow {}_{106}^{257}\text{Sg} + 3{}_0^1\text{n}$ ${}_{98}^{249}\text{Cf} + {}_8^{18}\text{O} \longrightarrow {}_{106}^{263}\text{Sg} + 4{}_0^1\text{n}$
meitnerium	Mt	107	${}_{83}^{209}\text{Bi} + {}_{26}^{58}\text{Fe} \longrightarrow {}_{109}^{266}\text{Mt} + {}_0^1\text{n}$

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