20.10: Nuclear Transmutation and Transuranium Elements

One of the goals of the early chemists of the Middle Ages, who were known as *alchemists*, was to transform ordinary metals into gold. Many alchemists hoped to turn low-cost metals, such as lead or tin, into precious metals and in this way become wealthy. These alchemists were never successful because their attempts were merely chemical—they mixed different metals together or tried to get them to react with other substances in order to turn them into gold. In a chemical reaction, an element retains its identity, so a less valuable metal—such as lead—always remains lead, even when it forms a compound with another element.

Nuclear reactions, in contrast to chemical reactions, result in the transformation of one element into another, a process known as **transmutation**. We have already seen how this occurs in radioactive decay, in fission, and in fusion. In addition, other nuclear reactions that transmute elements are possible. For example, in 1919 Ernest Rutherford bombarded nitrogen-17 with alpha particles to form oxygen:

$$ {}^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H} $$

Iréne Joliot-Curie (1897–1956), who was the daughter of Marie Curie, and her husband Frédéric Joliot (1900–1958), bombarded aluminum-27 with alpha particles to form phosphorus:

$$ {}^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{30}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n} $$

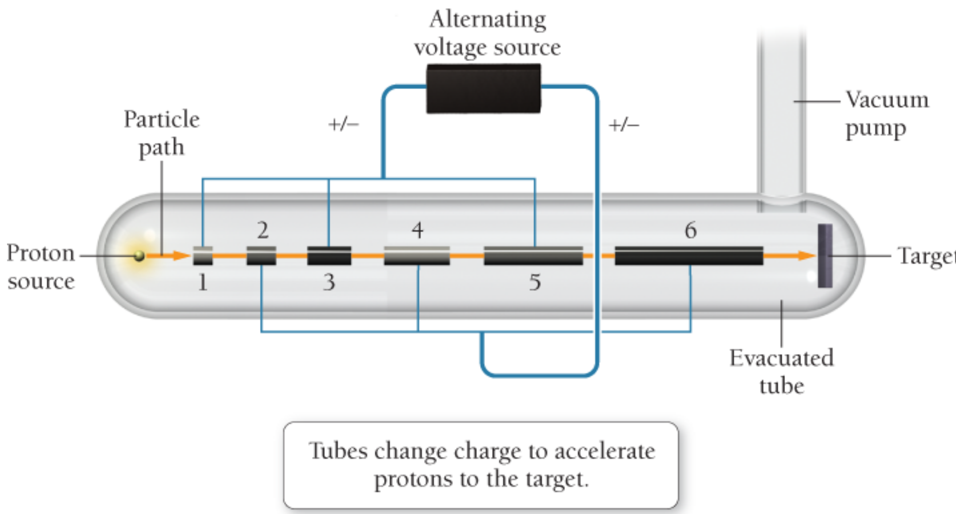
The Joliot-Curies won the 1935 Nobel Prize in Chemistry for their work on nuclear transmutation.

In the 1930s, scientists began building devices that accelerate particles to high velocities, opening the door to even more possibilities. These devices are generally of two types, the **linear accelerator** and the **cyclotron**.

In a *single-stage linear accelerator*, a charged particle such as a proton is accelerated in an evacuated tube. The accelerating force is provided by a potential difference (or voltage) between the ends of the tube. In *multistage linear accelerators*, such as the Stanford Linear Accelerator (SLAC) at Stanford University, a series of tubes of increasing length is connected to a source of alternating voltage, as shown in Figure 20.15. The voltage alternates in such a way that, as a positively charged particle leaves a particular tube, that tube becomes positively charged, repelling the particle to the next tube. At the same time, the tube that the particle is now approaching becomes negatively charged, pulling the particle toward it. This continues throughout the linear accelerator, allowing the particle to be accelerated to velocities up to 90% of the speed of light. When particles of this speed collide with a target, they produce a shower of subatomic particles that can be studied. For example, researchers using the Stanford Linear Accelerator were awarded the 1990 Nobel Prize in Physics for discovering evidence that protons and neutrons were composed of still smaller subatomic particles called *quarks*.

Figure 20.15 The Linear Accelerator

In a multistage linear accelerator, the charge on successive tubes (numbered 1–6 in this diagram) is rapidly alternated in such a way that as a positively charged particle leaves a particular tube, that tube becomes positively charged, repelling the particle toward the next tube. At the same time, the tube that the particle is now approaching becomes negatively charged, pulling the particle toward it. This process repeats itself through a number of tubes until the particle has been accelerated to a high velocity.

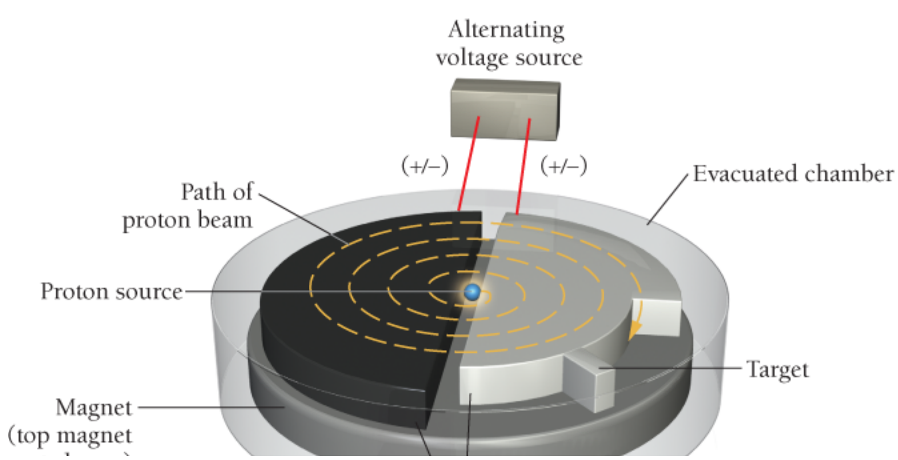


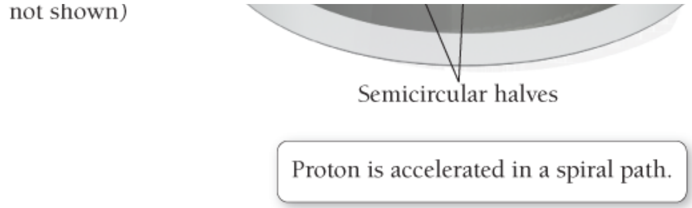
The Stanford Linear Accelerator is located at Stanford University in California.

In a cyclotron, a similarly alternating voltage is used to accelerate a charged particle, only this time the alternating voltage is applied between the two semicircular halves of the cyclotron (Figure 20.16). A charged particle originally in the middle of the two semicircles is accelerated back and forth between them. Additional magnets cause the particle to move in a spiral path. As the charged particle spirals out from the center, it gains speed and eventually exits the cyclotron aimed at the target.

Figure 20.16 The Cyclotron

In a cyclotron, two semicircular D-shaped structures are subjected to an alternating voltage. A charged particle (such as a proton), starting from a point between the two, is accelerated back and forth between them, while additional magnets cause the particle to move in a spiral path.





The Fermi National Accelerator Laboratory complex in Batavia, Illinois, includes two cyclotrons in a figure-8 configuration.

With linear accelerators or cyclotrons, all sorts of nuclear transmutations can be achieved. In this way, scientists have made nuclides that don't normally exist in nature. For example, uranium-238 can be made to collide with carbon-12 to form an element with atomic number 98:

$$^{238}_{92}\mathrm{U} + ^{12}_{6}\mathrm{C} \rightarrow ^{244}_{98}\mathrm{Cf} + 6^{1}_{0}\mathrm{n}$$

This element was named californium (Cf) because it was first produced (by a slightly different nuclear reaction) at the University of California at Berkeley. Many other nuclides with atomic numbers larger than that of uranium have been synthesized since the 1940s. These synthetic elements—called transuranium elements—have been added to the periodic table.

> Most synthetic elements are unstable and have very short half-lives. Some exist for only fractions of a second after they are made.

Conceptual Connection 20.4 Nuclear Transformations

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