

# Chapter 7

## Transmutation of the Elements

### 7.1 The Electron, X-rays and Radium

When voltage is applied to the ends of a glass tube filled with rarefied gas, an arc of light passes from the cathode – negative end – of the gas tube to the other end – the anode, which is positive. If vacuum pumps are used to reduce the gas pressure in the glass tubes, they cease to glow inside, but the glass shines where the invisible cathode rays apparently are striking it.

The French scientist Jean Perrin (1870–1942) used a magnet to deflect the location of the glowing spot on the glass, suggesting that the unseen streams of “rays” were beams of negatively charged particles (Perrin 1895). A magnetic field deflects a negative charge in one direction and a positive charge in the other direction, and the size of the deflection depends on the mass of the charged particle, its velocity, and the strength of the magnetic field. The British physicist Joseph John Thomson (1856–1940) subsequently used both electric and magnetic fields to measure the deflection of the beams of charged particles, now called *electrons*.

The deflection experiments worked this way: an electrical field produces a force that bends a beam of electrons in the direction of the field, toward positive and away from negative electrodes. By measuring the deviation from the original direction of motion, the charge to mass ratio  $e/m$  can be determined. Because the deflection also depends on the velocity of the electrons, another measurement was needed, which was accomplished by placing a magnet near the electron beam. Combining both the electrical and magnetic experiments determines the charge to mass ratio of the electron. So, it was from this ratio and the fundamental unit of charge that the mass of the electron was determined. Thomson concluded that the electron is much less massive than any atom. In fact, it is roughly 1,000 times less massive than the lightest atom, hydrogen (Thomson 1897a, b, 1903).

Meanwhile, the German physics professor Wilhelm Röntgen (1845–1923) inadvertently left some wrapped, unexposed photographic plates near a glowing gas tube that he was studying. Later, he found that the plates were fogged and that

this always happened when other new plates were left near the apparatus. Röntgen concluded that invisible rays were passing out of the tube and fogging the plates.

In those days, photographs were taken with glass plates covered with a light-sensitive emulsion of silver salts. This preceded the use of photographic film, which has been replaced by the charge-coupled devices used in digital cameras.

To remove any light, Röntgen enclosed the electrical discharge tube in black cardboard, and noticed a glow coming from a nearby sheet of paper coated with a substance (barium platinocyanide) known to shine in strong light – but there was no light to make it glow. The cause seemed to be the same invisible rays that fogged the photographic plates. Moreover, when Röntgen's wife placed her hand between the electrified gas tube and a photographic plate, the developed photograph showed the bones of her hand and the ring she was wearing (Röntgen 1896).

The report of these previously unknown and penetrating rays caused a public sensation, for they could see inside humans and reveal the invisible. The rays were able to penetrate skin and muscle, detecting human bones, which revolutionized medicine.

No one knew what these mysterious, penetrating emissions were, so Röntgen called them x-rays, using the mathematical designation x for something unknown. Subsequent investigations eventually showed that the x-rays are electromagnetic radiation of very short wavelength and high photon energy.

In 1896, at the Sorbonne in Paris, Henri Becquerel (1852–1908) was investigating fluorescent substances that could collect the energy of light and remain luminous after the light source was removed. Uranium salts, for example, glowed in the dark, and Becquerel thought that they also might emit x-rays after being stimulated by sunlight. However, clouds shut out the Sun, so he tossed the packet of uranium salts into a drawer in his worktable.

A box of unexposed photographic plates had been left in the drawer, wrapped in thick black paper and never opened; this led to another accidental discovery. When Becquerel took out the plates a few days later and developed photographs taken with them, he found that they were ruined, as if they had previously been exposed to light. The uranium salts were emitting unseen rays that could affect the plates, even in pitch darkness. Becquerel called the invisible, highly penetrating phenomenon uranic rays (Becquerel 1896). For a time they were called Becquerel rays, and eventually they became known as radioactive rays, but for decades, no one knew exactly what they were.

The new type of rays passed without difficulty through a covered box of photographic plates, but they might not penetrate metal. Becquerel repeated the experiment with an iron key placed between new photographic plates and the uranium. When the plates were developed, they showed the silhouette of the key. This indicted that the uranium was emitting rays that were unable to pass through the iron, even though they could penetrate dark paper that blocks ordinary light. In this respect, the uranium rays resembled x-rays; but unlike x-rays, the uranium was emitting rays spontaneously without any previous excitation by sunlight or electricity.

Hearing of Becquerel's discovery, Pierre Curie (1859–1906), also a professor of physics at the Sorbonne, and the young graduate student he recently had married, Manya (Marie) Curie (1867–1934), began to investigate the new type of rays. Madame Curie wanted to know if uranium was the only element that emitted the mysterious rays, and developed methods to measure the amounts being released. To her surprise, she found that impure uranium ores emitted more rays than could be explained in terms of the uranium they contained. The couple began a laborious two-year search for the unknown emitters; from one ton of the uranium ore known as pitchblende they extracted just a few grams of powerful new elements that had not been known previously (Curie 1898; Curie and Curie 1898). One was called radium and the other polonium, after Marie's native Poland.

Radium is one million times more radioactive than uranium, which – in the terminology of the time – meant that radium is emitting the penetrating rays more intensely than uranium, not that either substance emits radio waves. Crystals containing radium can light up an otherwise dark room, and also burn the skin, as Curie discovered to his dismay.

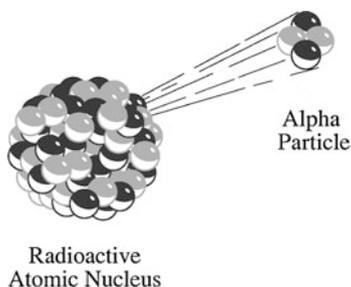
## 7.2 Radioactivity

At the time of their discovery, no one knew exactly what radioactive rays were, where their energy came from, or why the radioactive materials kept pouring out energy. Moreover, the amount of energy being released by radium was difficult to explain, for it far surpassed anything that had been achieved by chemical reactions. And, it is a natural process that happens all the time in the ground on which we stand.

It was the English physicist Ernest Rutherford (1871–1937) who found that the source of radioactive energy must come from the interior of the radioactive atoms. These very heavy atoms were unstable, disintegrating all by themselves and slowly leaking energy from their interiors in spontaneous transmutation (Rutherford 1904).

Rutherford previously found that the radioactive rays emitted by uranium included at least two distinct types, termed *alpha rays* and *beta rays* (Rutherford 1899). These rays are not waves of radiation; they instead are beams of energetic, fast-moving particles. By using electrical and magnetic fields, the two types of particles could be separated and their physical properties examined. The directions in which the beams were deflected indicated the sign of their electrical charge, and the magnitude of the deflection provided a measure of both the charge and the mass.

The most energetic particles emitted by radioactive substances are alpha particles (Ramsay and Soddy 1903). Alpha particles carry a double dose of positively charged protons, and they move at astonishingly high speeds – about  $1.5 \times 10^7 \text{ m s}^{-1}$ , or one-twentieth the speed of light (Rutherford 1911). This corresponds to a typical kinetic energy of about 5 MeV, or five mega-electron-volts and  $8.01 \times 10^{-13} \text{ J}$ . Rutherford and his colleagues eventually showed that an alpha particle is nothing



**Fig. 7.1 Radioactive alpha decay** An unstable, heavy nucleus of a radioactive element can disintegrate or decay into a stable, lighter nucleus, with the emission of an alpha particle that carries mass away from the heavy nucleus during its decay. The subatomic alpha particle consists of two protons and two neutrons. The nucleus of a helium atom is an alpha particle. Radioactive alpha decay of an individual heavy element such as uranium does not occur very often, on average. We would have to wait 4.47 billion years for half of a rock of uranium to change into lead by emitting alpha particles. (From “The Life and Death of Stars” by Kenneth R. Lang, published by Cambridge University Press, 2012. Reprinted with permission.)

more than the nucleus of the helium atom, containing two protons and two neutrons. The alpha particles were being emitted by a heavy, unstable atom that was turning spontaneously into a slightly lighter atom, without any interactions with another particle or radiation from outside the atom (Fig. 7.1).

Radioactive decay is occasionally accompanied by the emission of charged beta rays, which make an electronic adjustment to an atom’s nucleus without significantly changing its mass. Beta rays consist of negatively charged particles of low mass, which eventually were identified as high-speed electrons.

The ejection of alpha and beta particles often is accompanied by the emission of powerful electromagnetic radiation, akin to x-rays but with even shorter wavelength and greater energy (Villard 1900; Rutherford and Andrade 1914). Because the energetic radiation, called gamma rays and designated  $\gamma$ , is not charged, electrical or magnetic fields do not deflect it.

Working with the young chemist Frederick Soddy (1877–1956), Rutherford found that radioactive atoms continued to disintegrate into other pieces after the emission of an alpha particle (Rutherford and Soddy 1902, 1903). Uranium, for example, initially turned into thorium, which also was radioactive and released other substances, including gaseous radon.

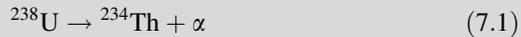
However, the progressive disintegration of heavy, unstable elements does not continue forever. As radioactive decay progresses, the inner parts of an atom rearrange into greater stability, eventually reaching an equilibrium that does not decay. For uranium, this stable endpoint is lead.

A simplified notation, described in Focus 7.1, clarifies how these complex chains of radioactive decay work.

### Focus 7.1 Nuclear nomenclatures

The number of protons in a nucleus is denoted by the atomic number  $Z$ . They account for the charge of the nucleus but not for all of its mass. A nucleus of any element except hydrogen has about twice the mass of the sum of its protons. The extra mass is due to neutral, or uncharged, particles called neutrons, each with about the same mass as a proton. The mass of the nucleus is specified by the mass number  $A = N + Z$ , where  $N$  is the number of neutrons; the mass number  $A$  also gives the number of nucleons in the nucleus, which is the sum of the number of protons and the number of neutrons.

Letters denote the nuclei and other subatomic particles. Both a letter and a superscript, the mass number  $A$ , designate a nucleus. An arrow  $\rightarrow$  specifies the reaction. Nuclei on the left side of the arrow react to form products given on the right side of the arrow. The alpha decay of uranium, for example, is given by



or



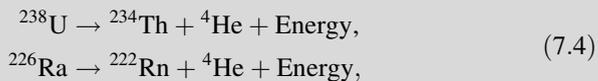
where  $U$  denotes a nucleus of uranium,  $Th$  indicates a nucleus of thorium, and the alpha particle  $\alpha$  is the nucleus of the helium atom, also designated  ${}^4\text{He}$ .

Another way of describing the alpha decay of a nucleus of mass number  $A$  and atomic number  $Z$ , the number of protons, is:



where the helium nucleus  $\alpha$ , with  $A = 4$  and  $Z = 2$ , balances out both the mass and charge on each side of the reaction. The total sum of neutrons and protons on the left side of the arrow is equal to the total sum on the right side; it's just that they have been redistributed.

The spontaneous decay of the uranium, U, radium, Ra, and polonium, Po, nuclei can be represented by:



and



where the arrow denotes the decay of the nucleus on the left side to the nuclei on the right side, the superscripts denote the number of protons and

neutrons in the nucleus, *Th* denotes the thorium nucleus, *Rn* denotes the nucleus of radon, *Pb* denotes the lead nucleus, and *He* is the helium nucleus, the alpha particle. Both radium and polonium are also natural products in the decay chain of radioactive uranium.

### 7.3 Tunneling Out of the Atomic Nucleus

Why don't the nuclei of the radioactive atoms decay completely all at once? Or to ask a related question, how have the nuclei of so many uranium atoms managed to retain their alpha particles? After all, there is still plenty of uranium around billions of years after the Earth formed, continuing to make the rocks and soil around us radioactive. The reason is that it takes significant energy to break free of the strong forces that bind the protons and neutrons together in the nucleus of an atom. They are locked so firmly within the nucleus that exceptional force must be applied to dislodge them.

In fact, the escape of an alpha particle from an atomic nucleus seemed impossible from the viewpoint of classical physics. The forces holding the particle inside the nucleus are so strong that the energy required to overcome them is enormous. It is as if the atomic nucleus is surrounded by tall walls with an energy much higher than that of the alpha particles.

The Russian physicist George Gamow (1904–1968) resolved this paradox in 1928, by using the uncertain, probabilistic nature of quantum theory to explain the mechanism of radioactive decay. Quantum theory indicated that the location of a tiny subatomic particle is not defined precisely. It might be anywhere, although with decreasing probability at regions far from the most likely location.

This explains the escape of alpha particles from the nuclei of radioactive atoms such as uranium. These particles usually lack the energy to overcome the nuclear barrier, but some have a small probability of escaping to the outside world. And because there is some probability that they will “leak through” the nuclear walls, eventually some do. The chance of escaping the atomic nucleus increases with the kinetic energy of the subatomic particle and decreases with its electrical charge.

Not all nuclei are radioactive. For a nucleus to be unstable there has to be available a final state in which the sum of the masses of the decay products is less than the mass of the initial nucleus.

So, how fast is the rate of decay? Gamow's (1928) quantum-mechanical formula for the “transparency” of the nuclear walls was in good agreement with Rutherford's suggestion that the number of radioactive atoms,  $N$ , in a rock changes with time,  $t$ , since its solidification with a constant rate of decay according to the equation (Rutherford 1900):

$$\frac{dN}{dt} = -\lambda N \quad (7.6)$$

where the radioactive decay constant  $\lambda = 0.693/\tau_{1/2} = \ln 2/\tau_{1/2}$  and  $\tau_{1/2}$  is the half-life of the radioactive species.

The decay rates of various radioactive substances differ. The nuclei of uranium can retain their alpha particles for billions of years, whereas other radioactive nuclei eject them in a matter of seconds. These rates are quantified in terms of the nuclear half-life, which is the time needed for a given amount of a radioactive substance to decay to half of its initial value.

The decay is probabilistic, governed by the rules of quantum mechanics that describe a random, slow, and statistical decay. On the level of a single atom, it is impossible to predict when a given atom will decay, and the probability that a given unstable atom decays is the same for all atoms of that type, independent of age. For numerous identical atoms, the decay rate is predictable using quantum theory, and that rate depends on the radioactive element under consideration.

At almost the same time as Gamow's discovery, the British physicist Ronald W. Gurney (1898–1953) and the American physicist Edward U. Condon (1902–1974) developed a similar explanation for spontaneous radioactive decay (Gurney and Condon 1928).

The decay equation integrates to give the number of radioactive atoms,  $N(t)$  at time  $t$ :

$$N(t) = N_0 \exp(-\lambda t) = N_0 \exp\left(\frac{-0.693 t}{\tau_{1/2}}\right), \quad (7.7)$$

where  $N_0$  is the number of atoms at time  $t = 0$ , the time of solidification,  $\lambda$  is the radioactive decay constant,  $\tau_{1/2}$  is the half-life of the radioactive atom, and 0.693 is the natural logarithm of 2 denoted  $\ln 2$ .

The mean lifetime,  $\tau$ , of a radioactive atom is the inverse of the decay constant, or

$$\tau = \frac{1}{\lambda} = \frac{\tau_{1/2}}{\ln 2} = \frac{\tau_{1/2}}{0.693}, \quad (7.8)$$

where the radioactive decay constant  $\lambda = 0.693/\tau_{1/2} = \ln(2)/\tau_{1/2}$ , and  $\tau_{1/2}$  is the half-life of the atom.

The half-life is the time required for a quantity of radioactive atoms to fall to half its value as measured at the beginning of the time period, following the exponential decay equation. For example, uranium 238 decays into thorium 234 with the emission of an alpha particle and a half-life of  $4.46 \times 10^9$  years, or 4.46 billion years. The thorium eventually decays into radium 226, which itself decays into radon gas with the emission of another alpha particle and a half-life of 1,601 years. The radon eventually decays into polonium 210, which decays into stable lead 206 with the emission of another alpha particle and a half-life of just 138.4 days.

**Table 7.1** Long-lived radioactive isotopes used for dating

Radioactive parent	Stable daughter	Half-life (years)
Rubidium (Rb) 187	Strontium (Sr) 87	48.8 billion
Rhenium (Re) 187	Osmium (Os) 187	44 billion
Lutetium (Lu) 176	Halfnium (Hf) 176	35.7 billion
Thorium (Th) 232	Lead (Pb) 208	14.05 billion
Uranium (U) 238	Lead (Pb) 206	4.47 billion
Potassium (K) 40	Argon (Ar) 40	1.27 billion
Samarium (Sm) 146	Neodymium (Nd) 142	0.10 billion
Uranium (U) 235	Lead (Pb) 207	704 million
Plutonium (Pu) 244	Thorium (Th) 232	83 million
Iodine (I) 129	Xenon (Xe) 129	16 million
Palladium (Pd) 107	Silver (Ag) 107	6.5 million
Manganese (Mn) 53	Chromium (Cr) 53	3.7 million
Aluminum (Al) 26	Magnesium (Mg) 26	0.72 million

The parent radioactive atoms eventually decay into stable daughters, and the amount of the daughter steadily increases at the expense of the parent.

Half-lives for the decay of long-lived radioactive parent isotopes are listed in Table 7.1 together with the stable daughter isotopes. As an example, it takes 4.47 billion years for half the atoms in a lump of uranium to change into lead.

This provides us with a way of measuring the age of the solar system. You just measure the relative amounts of radioactive parents and non-radioactive daughters. When this ratio is combined with the known rates of radioactive decay, the time since the rock solidified and locked in the radioactive atoms is found.

The daughters can escape easily when the rock is molten; only when it cools and solidifies do they start to accumulate. For this reason, the age determined for a rock is actually the time since the rock became solid. If the rock is remelted, for example by the impact of a meteorite, its radioactive clock is reset and the age will measure the time since the last solidification.

Radioactive dating of primitive meteorites, ancient rocks returned from the Moon, and deep ocean sediments indicates an age of about 4.6 billion years. These relics have remained unaffected by the geological erosion processes that removed the primordial record from most terrestrial rocks. If the solar system originated as one entity, then this also should be the approximate age of the Sun and the rest of the solar system (Focus 7.2).

### Focus 7.2 The age of the solar system

Radioactive elements can be used to clock the age of rocks on the Earth's surface, meteorites, and lunar rock samples. The number of radioactive atoms in the rock will be halved in a time equal to the half-life. Radioactive uranium,  $U^{238}$ , decays, for example, into lead,  $Pb^{206}$  (which is stable), with a half-life of about 4.47 billion years; so every 4.47 billion years the amount of uranium-238 in a rock will be halved. We can apply the equations to  $U^{238}$ ,

and express the abundance in terms of another kind of lead,  $\text{Pb}^{204}$ , which is not a radioactive decay product. If a terrestrial rock, lunar sample, or a non-terrestrial meteorite became a closed system at time  $t = 0$ , then the present abundances of lead and uranium are related by the equation:

$$\left(\frac{\text{Pb}^{206}}{\text{Pb}^{204}}\right)_t = \left(\frac{\text{U}^{238}}{\text{Pb}^{204}}\right)_t [\exp(\lambda_{238} t) - 1] + \left(\frac{\text{Pb}^{206}}{\text{Pb}^{204}}\right)_0, \quad (7.9)$$

where the subscripts  $t$  and  $0$  denote the present and initial abundance, respectively.

If all of the rock samples have the same initial  $\text{Pb}^{206}/\text{Pb}^{204}$  abundance, and if all of them have the same age,  $t$ , then a plot of  $(\text{Pb}^{206}/\text{Pb}^{204})_t$  against  $(\text{U}^{238}/\text{Pb}^{204})_t$  should lie in a straight line of slope  $[\exp(\lambda_{238} t) - 1]$ . Such a plot is called an isochron. If a system formed  $t$  years ago and initially contained no lead, then a curve of the ratios  $^{207}\text{Pb}/^{206}\text{Pb}$  and  $^{238}\text{U}/^{206}\text{Pb}$  also provides the age  $t$ .

Radioactive dating has been used to determine an age of carbonaceous chondrite meteorites of  $t = 4.566 \pm 0.002$  billion years, where one billion years =  $10^9$  years = one Gigayear, abbreviated Gyr (Patterson 1956, Birck 1990). Radioactive dating of the oldest rocks returned from the Moon indicate an age of about 4.5 billion years (Wasserburg et al. 1977), and deep sediments in the Earth's oceans are dated at 4.55 billion years. Rounding off the numbers and allowing for possible systematic errors, we can say that the Earth, Moon and meteorites solidified at the same time some 4.6 billion years ago, with an uncertainty of no more than 0.1 billion years. If the solar system originated as one entity, then this should also be the approximate age of the Sun and the rest of the solar system.

Despite Gamow's tunneling discovery, our understanding of radioactivity was still incomplete; there was something wrong with the way the beta rays were behaving. This resulted in the discovery of an entirely new particle – the electron neutrino.

## 7.4 The Electron and the Neutrino

When first discovered, the electrons emitted from radioactive elements were called beta rays, to distinguish them from alpha rays (helium nuclei) and gamma rays (high-energy radiation) that also are emitted during radioactive decay processes. From their measured charge and mass, it was discovered that the betas are not rays at all but instead ordinary electrons moving at nearly the speed of light. The emission of high-speed electrons by a radioactive element is known as beta decay.

Detailed measurements of the high-speed electrons, given off during radioactive decay, seemed to violate a fundamental principle of physics known as the conservation of energy. According to this rule, the total energy of a system must remain unchanged unless acted on by an outside force. We know of no process that disobeys this principle.

Nevertheless, the sum of the energy of the beta decay nucleus and the energy of the emitted electrons sometimes turned out to be less energy than the amount of energy lost by the initial nucleus. Careful measurements failed to turn up the missing energy, which seemed to have vanished into thin air, suggesting that energy might not be conserved during beta decay. The eminent Danish physicist Niels Bohr (1885–1962) even proposed that the conservation of energy law was being violated on the atomic scale, suggesting that the beta decay observations may force us to renounce the very idea of energy balance (Bohr 1930).

However, it turned out that a mysterious, invisible particle was spiriting away the missing energy. It was the elusive neutrino, whose existence was postulated by Wolfgang Pauli (1900–1958), a brilliant Austrian physicist. Pauli proposed a “desperate way out” of the energy crisis, speculating that an electrically neutral particle, produced at the same time as the electron, carried off the remaining energy (Pauli 1930, 1933). The sum of the energies remains constant during the beta decay, so the energy is balanced and the principle of conservation of energy is saved.

Pauli thought he had done “a terrible thing”, for his desperate remedy postulated an invisible particle that could not be detected. Dubbed the *neutrino*, or “little neutral one” by the Italian physicist Enrico Fermi (1901–1954), the new particle could not be observed with the technology of the day, since the neutrino is electrically neutral, has almost no mass, and moves at nearly the speed of light. Therefore the hypothetical neutrinos were removing energy that would never be seen again. (Even in Pauli and Fermi’s time, the observed high-energy shape of the emitted electron’s energy spectrum indicated that the mass of the neutrino is either zero or very small relative to the mass of the electron).

Unlike light or any other form of radiation, neutrinos can move nearly unimpeded through any amount of material, even the entire universe. In the parlance of modern physics, neutrinos are characterized by a weak interaction with anything in the material world.

As beautifully described by Fermi, the decay process occurs when the neutron in a radioactive nucleus transforms into a proton with the simultaneous emission of an energetic electron and a high-speed neutrino (Fermi 1934). When left alone outside a nucleus, a neutron will, in fact, self-destruct in about 10 min into a proton, plus an electron to balance the charge, and a neutrino to help remove the energy.

We can write the radioactive beta decay reaction as



where  $n$  denotes a neutron,  $p$  is a proton,  $e^-$  is an electron, and  $\bar{\nu}_e$  denotes the anti-electron neutrino, or the anti-particle of the electron neutrino. The proton and electron have equal charges of opposite sign, so their charges cancel to match the uncharged neutron – provided that the neutrino has no charge. The electron  $e^-$  is sometimes denoted beta minus ( $\beta^-$ ) to denote the emission of the beta particle, the electron. The reaction was also known as negative beta decay, with the negative standing for the negative charge of the negative beta particle, the electron.

The nuclear reaction for negative beta decay can be written:

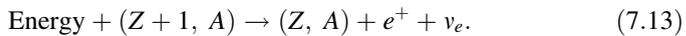


where  $(Z, A)$  denotes a nucleus of atomic number or charge  $Z$  and mass number  $A$ .

If a positron, denoted  $e^+$ , is emitted, the reaction is written:



where energy has been supplied to fuel the reaction and  $\nu_e$  denotes the electron neutrino. Sometimes the positron in this reaction is denoted beta plus ( $\beta^+$ ). Unlike  $\beta^-$  decay, the positive beta decay is not a spontaneous reaction that occurs in isolation because it requires energy, the mass of the neutron being slightly greater than the mass of the proton. The nuclear reaction for positive beta decay is



As far as anyone could tell, an atomic nucleus consists only of neutrons and protons, so the electron and neutrino seemed to come out of nowhere. They do not reside within the nucleus and are created at the time of nuclear transformation. No one knew exactly how the neutrinos formed.

How do you observe something that spontaneously appears out of nowhere and is so close to being nothing at all? Calculations suggested that the probability of a neutrino interacting with matter, so that the effect might be seen, is so incredibly small that no one could ever detect it. To see one neutrino, we would have to produce enormous numbers at about the same time, and build a massive detector to increase the chances of detecting it. Although almost all of the neutrinos still would pass through any amount of matter unhindered and undetected, a rare collision with other subatomic particles might leave a trace.

Nuclear reactors produce large numbers of neutrinos, and if a massive detector is placed near a large nuclear reactor, with appropriate shielding from extraneous signals, the telltale sign of the hypothetical neutrino may be barely observed.

The existence of the neutrino was finally proven by Project Poltergeist, an experiment designed by Clyde L. Cowan (1919–1974) and Frederick Reines (1918–1998) of the Los Alamos National Laboratory in New Mexico. They placed a 10-ton (10,000 L) tank of water next to a powerful nuclear reactor engaged in making plutonium for use in nuclear weapons. After shielding the neutrino trap underground and running it for about 100 days, Reines and Cowan detected a few synchronized flashes of gamma radiation that signaled the interaction of a few

neutrinos with the nuclear protons in water (Reines and Cowan 1953, Cowan et al. 1956).

The neutrinos themselves were not observed, and they never have been. Their presence was inferred by an exceedingly rare interaction. One of every billion billion, or  $10^{18}$ , neutrinos that passed through the water tank hit a proton, producing the telltale burst of radiation. Nearly four decades later, Reines received the 1995 Nobel Prize in Physics for the detection of the neutrino; but by that time however, Cowan had died and therefore could not share in the award.

As discussed in Chap. 8, the Sun emits copious amounts of neutrinos. Every second, trillions upon trillions of neutrinos that were produced inside the Sun pass right through the Earth without even noticing that it is there. The indestructible neutrinos interact so rarely with the material world that almost nothing ever happens to them. Billions of ghostly neutrinos from the Sun are passing right through us every second, even in our bedrooms at night, and they did not come through the door. The solar neutrinos travel right through the Earth, a building, and us, without our body noticing them or them noticing our body.

Moreover, when a minute number of the Sun's neutrinos were snared in massive underground detectors, fewer than expected were observed; this eventually led to a new understanding of the neutrino. For the time being, however, let us move on to energetic cosmic rays that are always entering the atmosphere from outer space.

## 7.5 Cosmic Rays

Subatomic particles are entering our atmosphere from all directions in interstellar space and moving at nearly the speed of light. The perpetual high-energy rain was discovered about a century ago, when the Austrian physicist Victor Franz Hess (1883–1964), an ardent amateur balloonist, measured the amount of ionization at different heights within our atmosphere (Hess 1912).

It was already known that radioactive rocks at the Earth's surface were emitting energetic "rays" – the alpha and beta particles – that ionize molecules in the atmosphere near the ground. It was expected that the ionizing rays would be absorbed completely after passing through sufficient quantities of the atmosphere. The measured ionization at first decreased with altitude, as expected from atmospheric absorption of energetic particles emitted by radioactive rocks. However, the ionization rate measured by Hess increased at even higher altitudes to levels exceeding that at the ground when the balloons rose to above 1 km in altitude (Hess 1912). This meant that some penetrating source of ionization came from beyond the Earth. By flying his balloons at night and during a solar eclipse, when the high-altitude signals persisted, Hess showed that they could not come from the Sun but rather from some other source.

The American physicist Robert A. Millikan (1868–1953) subsequently used high-altitude balloon measurements to confirm that the "radiation" comes from

beyond the terrestrial atmosphere, and he gave it the present name of *cosmic rays* (Millikan 1926; Millikan and Cameron 1926). Millikan believed the cosmic rays were gamma rays associated with the synthesis of heavy elements deep in space, the “birth cries” of new matter. We now know that cosmic rays are energetic charged particles, not radiation, and more likely the “death cries” of massive exploding stars.

Global measurements showed that cosmic rays are electrically charged. During an ocean voyage in 1927 and 1928, the Dutch physicist Jacob Clay (1882–1955), for example, found lower cosmic-ray intensity near the Earth’s Equator than at higher terrestrial latitudes; his results were confirmed and extended between 1930 and 1933 by Arthur H. Compton (1892–1962) of the University of Chicago (Clay 1932; Compton 1932). Compton conclusively demonstrated an increase in cosmic-ray intensity with terrestrial latitude, and also made measurements at mountain altitudes, where the increase with latitude was even stronger. His results indicated that cosmic rays must be electrically charged particles deflected by the Earth’s magnetic field toward its magnetic poles, which are close to the geographic ones.

The amount of cosmic rays entering the Earth’s atmosphere varies with the amount of solar activity over an 11 year cycle; the amount of cosmic rays increase when the solar activity decreases and vice versa. This inverse correlation has been named the Forbush effect, after Scott Forbush (1904–1984) who discovered it (Forbush 1950). It has been attributed to an enhancement in the interplanetary magnetic field originating from the Sun at times of increased solar activity (Davis 1955; Meyer et al. 1956); these magnetic fields divert the cosmic rays and keep them from encountering the Earth.

The charged cosmic-ray particles also are deflected and change direction during encounters with the interstellar magnetic field that winds its way among the stars. Therefore, we cannot look back along their incoming path and tell where cosmic rays originate; the direction of arrival shows only where they last changed course. The favored hypothesis, proposed by Walter Baade (1893–1960) and Fritz Zwicky (1898–1974), is that cosmic rays are accelerated to their tremendous energy during the supernova explosion of massive stars that have run out of thermonuclear fuel (Baade and Zwicky 1934a, b, c, d). Kulsrud et al. (1972) and Blandford and Ostriker (1980) have discussed the acceleration of cosmic rays in supernovae.

By the late 1940s, instruments carried by high-altitude balloons established that the most abundant cosmic ray particles arriving in the Earth’s upper atmosphere are protons – the nuclei of former hydrogen atoms – and the second most abundant particles are helium nuclei – the alpha particles. Cosmic-ray electrons arriving near the top of the atmosphere took longer to discover (Earl 1961), mainly because they are far less abundant than the cosmic-ray protons at a given energy.

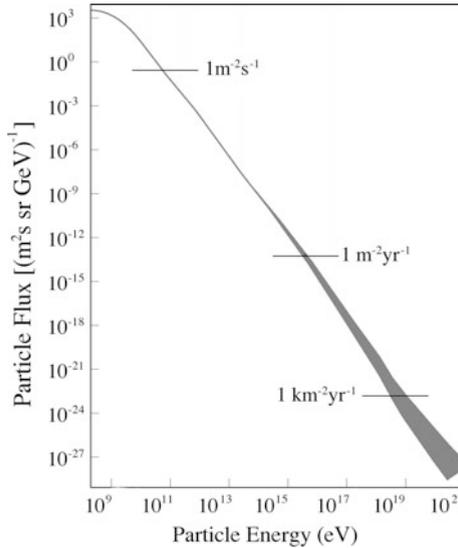
About 79 % of the cosmic rays arriving at the top of the Earth’s atmosphere are protons, about 14.7 % are nuclei of helium, and roughly 1 % is carbon and oxygen nuclei (Table 7.2).

Although they are relatively few in number, cosmic rays contain phenomenal amounts of energy. That energy usually is measured in units of electron volts, abbreviated eV – for conversion use  $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$ . The greatest flux of

**Table 7.2** Average fluxes of primary cosmic rays at the top of the atmosphere<sup>a</sup>

Type of nucleus	Flux (particles m <sup>-2</sup> s <sup>-1</sup> )
Hydrogen (protons)	640
Helium (alpha particles)	94
Carbon, oxygen	6

<sup>a</sup> The flux is in units of nuclei per square meter per second for particles with energies greater than 1.5 billion (1.5 × 10<sup>9</sup>) electron volts per nucleon, denoted 1.5 GeV per nucleon, arriving at the top of the atmosphere from directions within 30° of the vertical



**Fig. 7.2 Flux of cosmic rays** The energy spectrum of cosmic-ray particles striking the outer atmosphere of the Earth. The particle flux is plotted as a function of the particle energy in units of electron volts, abbreviated eV, where 1 eV = 1.602 × 10<sup>-19</sup> J and 1 GeV = 10<sup>9</sup> eV, or 1 billion eV. The most abundant cosmic-ray particles are protons with energies of about 1.5 × 10<sup>9</sup> eV. Every second about 640 enter every square meter of the Earth’s outer atmosphere. They probably are accelerated to high energy during the supernova explosions of massive stars. One cosmic-ray proton of 10<sup>10</sup> eV in energy enters each square meter of the Earth’s outer atmosphere every second. The more energetic cosmic ray particles of 10<sup>14</sup> eV are less abundant, with one per square meter every year. Solar flares can emit protons with energies of 10<sup>10</sup> eV or less, and these solar energetic particles can strike the Earth when the solar active region is on the near side of the Sun. Cosmic rays with low flux and very high energy, greater than 1 million billion eV, or 10<sup>15</sup> eV, may be of extragalactic origin. (From “The Life and Death of Stars” by Kenneth R. Lang, published by Cambridge University Press, 2012. Reprinted with permission.)

cosmic-ray protons arriving at the Earth have energies of 1–10 GeV, or at 1 billion (10<sup>9</sup>) to 10 billion (10<sup>10</sup>) electron volts of energy. By way of comparison, a helium nucleus, or alpha particle, emitted during radioactive decay reaches no more than a million eV in energy, or a thousand times less than that of a cosmic ray proton.

**Table 7.3** Particle speeds at different particle energies, expressed as fractions of the speed of light,  $c^a$ 

Particle kinetic energy (keV)	Electron speed (times $c$ )	Proton speed (times $c$ )
1 keV	0.063	0.0015
1,000 keV = 1 MeV	0.94	0.046
100,000 keV = 100 MeV	0.999987	0.43
1,000,000,000 keV = 1 GeV	0.99999987	0.88

<sup>a</sup> An energy of one kilo-electron volt is  $1 \text{ keV} = 1.6022 \times 10^{-16} \text{ J}$ , and the speed of light  $c = 2.99792458 \times 10^8 \text{ m s}^{-1}$

Cosmic rays do not all have the same energy, and some reach an energy of  $10^{20} \text{ eV}$ , more than 10 billion ( $10^{10}$ ) times the abundant ones; Kotera and Olinto (2011) have reviewed the astrophysics of ultra high-energy cosmic rays. The flux of the most common, lower-energy cosmic rays at  $10^9$ – $10^{10} \text{ eV}$  is greatest (Fig. 7.2).

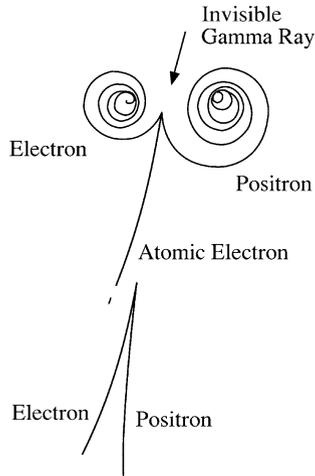
Even at an energy of  $10^9 \text{ eV}$ , a cosmic-ray proton must be traveling at 88 % of the speed of light (Table 7.3).

Cosmic rays enter the atmosphere with such great energies that they act like colossal atom destroyers, hitting molecules and their component atoms in the upper atmosphere and producing showers of subatomic debris, known as secondary cosmic-ray particles. This eventually led to the first observation of an energetic particle that does not belong to the atom. But first a method needed to be developed to detect the then-unknown particle.

Subatomic particles coming down through the atmosphere are detected near or at the ground by tracks in a cloud chamber, which creates a cloudy mist that precipitates as long thin bands of fog, along the trajectory of the particles. This is somewhat similar to the white vapor trails of jet aircraft, which record an airplane's movement in the sky. Fine water droplets condense from the jet exhaust fumes and create the elongated clouds.

The first cloud chamber, invented by Charles Thomas Rees Wilson (1869–1859), was very simple, consisting of a metallic cylinder with a glass cover and a piston that could be moved up and down from below, permitting air filled with water vapor to enter the space above it (Wilson 1911). When the piston was lowered quickly, the sudden expansion cooled the gas so that a mist formed in the chamber, like the foggy mist found high in the mountains. The water vapor in the chamber condensed or precipitated out on any ions present, making the ionized tracks of cosmic rays visible and showing where they had moved.

When the cloud chamber is placed between the poles of a strong magnet, the magnetic field exerts a force on any charged particle entering the chamber, which produces a curved particle track. When Carl Anderson (1945–2004), who was Millikan's student at the California Institute of Technology, built such a device, using a powerful electromagnet, he found in 1932 that a few of the cosmic ray showers produce two similar curved trajectories in opposite directions (Fig. 7.3). Further experiments revealed that an electron, which has a negative charge, was producing one of the curved tracks, whereas a particle with about the same mass as



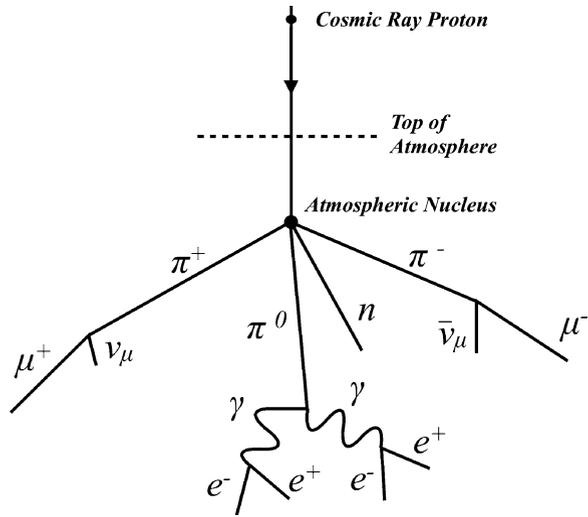
**Fig. 7.3 The electron and the positron** An invisible gamma-ray photon (*top*) produces an *electron* and a *positron* (short for positive electron), seen by *curved tracks* in a bubble chamber. Both the electron and the positron are bent into circular tracks by the instrument’s magnetic field, moving in opposite directions because of their opposite electrical charge and spiraling into a smaller circular motion as they lose energy. In this *upper pair*, some of the photon’s energy is taken up in displacing an atomic electron, which shoots off toward the *bottom left*. In the lower example, all of a gamma ray’s energy goes into the production of the electron–positron pair. As a result, these particles are more energetic than the *upper pair*, and their tracks do not curve so tightly in the chamber’s magnetic field. (Schematic of a Lawrence Berkeley Laboratory bubble-chamber image, reproduced by Frank Close, Michael Marten, and Christine Sutton in *The Particle Explosion*, New York: Oxford University Press 1987. (From “The Life and Death of Stars” by Kenneth R. Lang, published by Cambridge University Press, 2013. Reprinted with permission.)

the electron and a positive charge of the same amount but opposite sign as the electron was producing the track curved in the opposite direction. Anderson had discovered the positron, short for “positive electron” and the anti-matter counterpart of the electron (Anderson 1932a, 1933). The energetic cosmic rays had produced a new type of particle that had never been seen before!

Anderson received the Nobel Prize in Physics in 1936 for his discovery of the positron, sharing the award with Hess for his discovery of cosmic rays. Wilson had already received the recognition 9 years earlier, for his method of making the paths of electrically charged particles, the cosmic rays, visible by condensation of vapor.

As it turned out, Paul Adrien Maurice Dirac (1902–1984), then at Cambridge University, had predicted the existence of anti-matter (Dirac 1928). For Dirac, mathematical beauty was the most important aspect of any physical law describing nature. He noticed that equations that describe the electron have two solutions. Only one was needed to characterize the electron; the other solution specified a sort of mirror image of the electron – that is, an anti-particle, now called the

**Fig. 7.4 Cosmic ray shower** When a primary cosmic ray enters the Earth's atmosphere and collides with the nucleus of an atom in an atmospheric molecule, it can produce a shower of secondary subatomic particles. Here we show the most abundant cosmic ray particle, the proton, producing a neutron, designated  $n$ ; pions denoted by  $\pi$ , muons denoted by  $\mu$ , with the anti-muon-neutrino,  $\bar{\nu}_\mu$ , gamma rays, electrons  $e^-$  and positrons  $e^+$



*positron*. At the time of his discovery, Anderson nevertheless was unaware of Dirac's theoretical prediction of the positron.

The nuclear reaction that describes the creation of a positron is known as the inverse beta decay or positive beta decay, and it occurs when the energy of a colliding cosmic-ray particle is used to convert a proton,  $p$ , into a neutron,  $n$ . The reaction, written

$$\text{Energy} + p \rightarrow n + e^+ + \nu_e, \tag{7.14}$$

includes the production of the positron, denoted  $e^+$  or sometimes  $\beta^+$ , which carries away the charge of the proton, leaving a neutron with a slight increase in mass, and the electron neutrino, designated  $\nu_e$ , to balance the energy books on the two sides of the reaction.

Once created, anti-matter does not stay around for very long, for any anti-matter will promptly self-destruct when it encounters ordinary matter. When an electron and positron meet, they annihilate one another and disappear in a puff of energetic radiation. The electron-positron annihilation reaction is:

$$e^- + e^+ \rightarrow \gamma + \gamma, \tag{7.15}$$

where  $e^-$  is the electron, and  $\gamma$  denotes a gamma-ray photon, each with energy of 0.511 MeV equal to  $m_e c^2$ , which corresponds to the complete destruction of an electron of rest mass  $m_e$  where  $c$  is the speed of light. As discussed subsequently, this reaction helps to produce radiation in the core of the Sun, and also is observed during explosive flares on the visible solar disk.

When examining the cloud-chamber tracks of secondary particles produced by cosmic rays entering our atmosphere, scientists discovered other previously unknown subatomic particles (Fig. 7.4). There is the muon, denoted  $\mu$  (Anderson

**Table 7.4** Nobel Prizes related to experimental investigations of subatomic matter

Years	Person	Accomplishment
1927	C. T. R. Wilson (Scottish physicist)	For his method of making the paths of electrically charged particles visible by condensation of vapor
1936	Victor Franz Hess (Austrian physicist) Carl Anderson (American physicist)	For his discovery of cosmic radiation [now called cosmic rays] For his discovery of the positron
1938	Enrico Fermi (Italian physicist)	For his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons
1939	Ernest Lawrence (American physicist)	For the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements
1948	Patrick M. S. Blackett (English physicist)	For his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation
1950	Cecil Powell (English physicist)	For his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method
1951	John Cockcroft (English physicist) Ernest T. S. Walton (English physicist)	For their pioneering transmutation of atomic nuclei by artificially accelerated atomic particles
1959	Emilio Segrè (Italian-born American physicist) Owen Chamberlain (American physicist)	For their discovery of the antiproton
1995	Frederick Reines (American physicist)	For the detection of the neutrino
2002	Raymond Davis Jr. (American astrophysicist) Masatoshi Koshihba (Japanese astrophysicist)	For their pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos

and Neddermeyer 1937; Neddermeyer and Anderson 1937) and the pion, designated  $\pi$ , discovered using photographic emulsions to detect secondary cosmic ray particles at high altitudes, including the Pic Du Midi astronomical observatory (Lattes et al. 1947). The muon has a mass between that of the electron and the positron. The pion also has an intermediate mass. Hideki Yukawa (1907–1981) had predicted the existence of the pion more than a decade before its discovery, in his theory for the nuclear force (Yukawa 1935, 1937). Altogether, the investigations of x-rays, radioactivity, and cosmic rays resulted in quite a lot of recognition by the Nobel Prize in Physics (Table 7.4).

Atomic nuclei from outer space hit the upper atmosphere and produce a debris of pions. These soon decay into muons, which are always raining down to the

Earth. Many of the muons decay into electrons, positrons, and neutrinos during their flight through the atmosphere, and the very energetic muon neutrinos penetrate deep underground.

In 1998 a Japanese group reported that observations of muon neutrinos, generated by cosmic rays interacting with the atmosphere, indicate that neutrinos change type or flavor, oscillating between types as they travel through matter (Fukada et al. 1998a). There were roughly twice as many muon neutrinos coming from the atmosphere directly over their detector than those coming from the other side of the Earth. The muon neutrinos are produced in the atmosphere above every place on our planet, but some of them apparently disappeared while traveling through the Earth to arrive at the detector from below (Sect. 8.4).

In 2011, the *Alpha Magnetic Spectrometer* was carried by *Space Shuttle* to the *International Space Center*, where it will search for evidence of dark matter and anti-matter by measuring cosmic rays above the Earth's atmosphere.

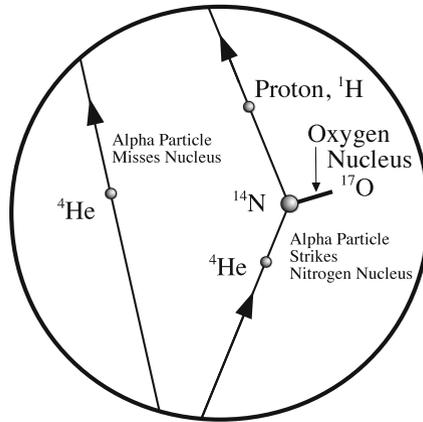
During the first half of the 20th century, investigations of cosmic rays revealed many unexpected aspects of subatomic particles, and this has inspired the construction of particle accelerators, which have been used to discover many other subatomic particles.

## 7.6 Nuclear Transformation by Bombardment

What happens if we turn radioactivity around and instead of watching the nucleus of an unstable heavy atom decay, we bombard a perfectly normal, lighter nucleus with very energetic particles? Perhaps this normally stable element could be transformed artificially on the Earth through such a nuclear bombardment. After all, that is what the cosmic rays were doing in the atmosphere, resulting in all kinds of surprises, turning some atoms into previously unknown, fundamental particles.

Medieval alchemists had been trying to change one element into another, like lead into gold, for centuries, but they always failed in their attempts because the chemical and thermal reactions they employed were nowhere near energetic enough to crack open the nucleus of an atom.

The first successful attempts to transform elements in the terrestrial laboratory occurred when Patrick M. S. Blackett (1897–1974), a recent graduate of Cambridge University, directed a beam of fast alpha particles, ejected by radioactive decay, into Wilson's cloud chamber. The chamber was filled with normal atmospheric air, which is composed mainly of nitrogen molecules. Blackett improved the cloud chamber so that the air expanded and cooled automatically, and he took automatic photographs of the alpha-particle tracks. Most of them passed straight through the chamber. However, after more than 23,000 photographs of alpha particles bombarding nitrogen in the cloud chamber, during a three-year period from 1921 to 1924, Blackett finally succeeded in recording just eight head-on collisions of alpha particles with the nuclei of nitrogen atoms (Blackett 1925).



**Fig. 7.5 Nuclear transformation** When an alpha particle, or helium nucleus denoted  ${}^4\text{He}$ , is sent through a cloud chamber, it usually passes right through it, with a trajectory that marks out a straight line. Occasionally, the alpha particle will strike the nucleus,  ${}^{14}\text{N}$ , of a nitrogen atom in the air within the chamber, transforming it into the nucleus,  ${}^{17}\text{O}$ , of an oxygen atom with the emission of a proton, the nucleus of a hydrogen atom and denoted  ${}^1\text{H}$ . Such a nuclear transformation was first observed in cloud chamber photographs taken in the early 1920s by Blackett (1897–1974). (From “The Life and Death of Stars” by Kenneth R. Lang, published by Cambridge University Press, 2013. Reprinted with permission.)

On each photograph, the track of an alpha particle suddenly stopped, being replaced with the fine, straight track of an ejected proton and the short, stubby recoil track of the struck nucleus (Fig. 7.5). However, there was no sign of the recoiling alpha particle. The collision had brought the alpha particle into the nitrogen nucleus, forming a nucleus of a form of oxygen. The reaction can be written as follows:



where the collision of an alpha particle, or helium nucleus  ${}^4\text{He}$ , with a nitrogen nucleus,  ${}^{14}\text{N}$ , gave rise to the nucleus of oxygen,  ${}^{17}\text{O}$ , and a proton, the nucleus of hydrogen,  ${}^1\text{H}$ . The old alchemist’s dream finally had been realized in a laboratory on the Earth, in which nuclear transformation had been induced and recorded.

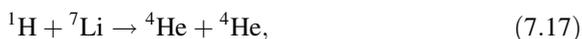
Enthusiastic scientists directed beams of alpha particles into many other elements, creating nuclear transformations similar to the one observed for nitrogen. When it came to heavier elements, with greater nuclear charge, however, a nuclear transformation could not be produced. The greater electrical repulsion of nuclei with atomic number  $Z$  greater than 18 always withstood the bombardment by alpha particles.

That is when Gamow’s paper on the decay of heavy radioactive nuclei had a decisive role (Gamow 1928). His calculations indicated that on rare occasions alpha particles could tunnel through the positively charged wall of a nucleus, but

that fast protons more easily overcome the barrier than slow, heavier nuclei. Because it has a smaller electrical charge, a proton suffers less nuclear repulsion when approaching a given nucleus, and therefore has a greater probability of penetrating it. Moreover, because the proton is four times less massive than an alpha particle, it might be easier to accelerate it to high speed.

Rutherford's student John Cockcroft (1897–1967) had studied electrical engineering, and used his background to build a machine that would accelerate the hydrogen nuclei, the protons, in very intense electrical fields. When applying 500,000 V, Cockcroft was able to produce a parallel beam of protons traveling at the speed of  $10^7$  m s<sup>-1</sup> or 1/30th the speed of light.

When bombarding lithium with high-energy protons, Cockcroft and his colleague Ernest T. S. Walton (1903–1995) turned the lithium nucleus into two alpha particles by the following nuclear reaction (Cockcroft and Walton 1932a):



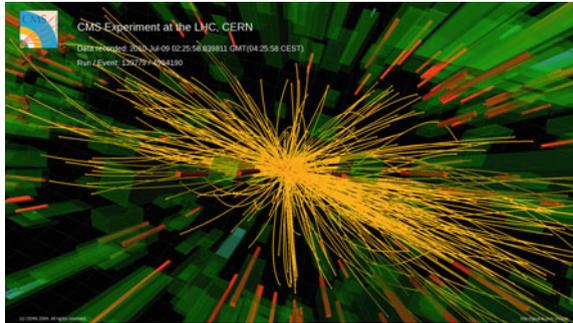
where  ${}^1\text{H}$  denotes the proton, the nucleus of a hydrogen atom,  ${}^7\text{Li}$  designates the lithium nucleus, and  ${}^4\text{He}$  denotes an alpha particle, the nucleus of the helium atom.

At about the same time, Ernest Lawrence (1901–1958), located at Berkeley University, invented the cyclotron, which used magnets to bend the path of a charged particle into a circular orbit that passed across an alternating and accelerating voltage. As the radius of the spiraling orbit increased, so did the particle's speed; therefore, the time to complete each orbit remained constant, and the particles were repeatedly accelerated in equal time intervals before directing them into a collision with something else. This is similar to pushing a child in a swing at the same part of its swinging motion, pumping it up to greater and greater speed.

Lawrence built increasingly larger cyclotrons at Berkeley's Radiation Laboratory, whirling the protons and other particles to faster and faster speeds. A cyclotron of just 0.69 m in diameter was able to accelerate protons, denoted  ${}^1\text{H}$  to 5 MeV in energy (Lawrence and Livingston 1932, 1934; Lawrence et al. 1932), and a 1.5 m cyclotron was used to accelerate deuterons, the nuclei of heavy hydrogen designated  ${}^2\text{H}$ , to an energy of 16 MeV (Lawrence and Cooksey 1936). His final cyclotron, with a diameter of nearly 5 m, could accelerate the deuterium nuclei of heavy hydrogen to energies of 195 MeV.

Deuteron bombardment of various elements, including beryllium, resulted in the creation of numerous neutrons and artificial radioactive isotopes. In 1939, the Nobel Prize in Physics was awarded to Lawrence for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements. It wasn't until 1951 that John Cockcroft and Ernest Walton received the prize for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles.

These early accomplishments stimulated the construction of increasingly powerful particle accelerators that accelerated particles to more and more energy. Eventually, accelerators were built that reached cosmic-ray energies, and this resulted in the discovery of new, previously unknown particles, such as the tau



**Fig. 7.6 Proton-proton collision** Two beams of protons have been whirled in opposite directions to nearly the speed of light, each with an energy of 7 trillion electron volts, or  $7 \text{ TeV} = 7 \times 10^{12} \text{ eV} = 1.12 \times 10^{-6} \text{ J}$ , and directed into collision with one another at CERN's Large Hadron Collider (LHC). This image displays the tracks of more than 100 charged particles as they fly away from the point of proton collision. Experiments with this instrument have provided evidence that is consistent with a new, previously unseen particle, named the *Higgs boson*, in the mass-energy range of  $10^{11} \text{ eV}$ . By studying the collision particle debris, including correlations among them, scientists hope to gain an improved knowledge of how subatomic particles interact at extremely high energies, including the hot, dense conditions only a small fraction of a second after the “big bang”. At the point of proton impact, temperatures of more than 1 million, or  $10^{12} \text{ K}$  are generated, exceeding 100,000 times the temperature at the center of the Sun. In particle physics, a hadron is a composite particle made of quarks held together by the strong force; the best-known hadrons are the protons and neutrons, which are components of atomic nuclei. CERN is a French acronym for the Conseil Européen pour la Recherche Nucléaire (the European Organization for Nuclear Research). The Compact Muon Solenoid (CMS) particle detector created this image. (Courtesy of CERN.)

lepton found as the result of particle collisions using the Stanford Linear Particle Accelerator (Perl et al. 1975, 1976).

Eventually, the 2 km-diameter Tevatron, an accelerator at the Fermi National Accelerator Laboratory, abbreviated Fermi lab, used thousands of electromagnets to whirl protons up to 1,000 GeV, or 1 TeV, of energy. By 2009 the Large Hadron Collider at the European Organization for Nuclear Research (known as CERN, an acronym for Conseil Européen pour la Recherche Nucléaire) was using superconducting magnets in a circular tunnel 27 km in circumference to produce two beams of protons moving in opposite directions, and eventually directed into collision with one another (Fig. 7.6). It has provided evidence consistent with another previously unknown particle, the Higgs boson.

In the meantime, on the eve of World War II (1939–1945), the German radiochemist Otto Hahn (1879–1968), who had been working with Fritz Strassmann (1902–1980) and Lise Meitner (1878–1968), showed that when uranium is bombarded with neutrons it could be split into two nearly equal fragments (Hahn and Strassmann 1939a, b). The process is known as nuclear fission, analogous to binary fission in the biological sciences. This was altogether different from the proton bombardment of much lighter nuclei, for the heavy uranium was

broken in two and released enormous amounts of energy in the process. Moreover, it also freed additional neutrons, which in turn can trigger the fission of neighboring nuclei, resulting in a runaway chain reaction if not properly controlled. When controlled, a nuclear chain reaction can be used to generate electricity in nuclear reactors; when uncontrolled, it has applications in nuclear weapons. Hahn received the 1944 Nobel Prize in Chemistry for the discovery of nuclear fission, but some historians believe that Meitner should have shared the award.

Meitner, who was in exile in Copenhagen, confirmed the fission of uranium by neutron bombardment (Meitner and Frish 1939), and the Danish physicist Niels Bohr described it to Albert Einstein (1875–1955), who had immigrated to the United States. By the time Einstein heard about uranium fission, World War II (1939–1945) had begun, and scientists feared that Nazi Germany would use the discovery to build an atomic bomb to conquer the world. In 1939 and 1940 Einstein wrote to the President of the United States, Franklin Roosevelt (1882–1945), encouraging a program that would achieve a nuclear chain reaction and to consider the development of “extremely powerful bombs” that the Germans also might be constructing. The concern was real, for it was later discovered that prominent German physicists, including Werner Heisenberg (1901–1976) and Carl von Weizsäcker (1912–2007), helped the Germans investigate the feasibility of constructing nuclear weapons during World War II.

In 1942, the famed American physicist J. Robert Oppenheimer (1904–1967) invited a small group of theoretical physicists to the University of California at Berkeley to discuss how an atomic bomb might be assembled. Within a year, they had all moved to Los Alamos, the secret laboratory in New Mexico where thousands of scientists, technicians, and military personnel worked under Oppenheimer’s enthusiastic direction to create the first atomic bomb.

Many of the best scientific minds in the country were involved, including Hans Bethe (1906–2005), head of the Los Alamos theoretical division; Richard Feynman (1918–1988), who worked on numerical calculations of bomb performance; and the Italian immigrant Enrico Fermi (1901–1954), who helped produce the first self-sustaining nuclear chain reaction. Another famous physicist, Philip Morrison (1915–2005), accompanied the first bombs all the way to their final flights, caring for them before they were dropped on Japan in 1945.

Some of the same scientists who developed the atomic bomb also showed how nuclear reactions deep inside the Sun and other stars makes them shine, while also producing most of the elements heavier than helium that are now found in the universe.