Chapter 19  Radioactivity and Nuclear Energy

1. The nucleus of an atom has little or no effect on the atom’s chemical properties. The chemical properties of an atom are determined by the number and arrangement of the atom’s electrons (which are outside the nucleus).

2. The radius of a typical atomic nucleus is on the order of 10^{-13} cm, which is about one hundred thousand times smaller than the radius of an atom overall.

3. The atomic number \(Z\) of a nucleus represents the number of protons present in the nucleus. The mass number \(A\) of a nucleus represents the total number of protons and neutrons in the nucleus. For example, for the nuclide \(^{13}\text{C}\), with six protons and seven neutrons, we have \(Z = 6\) and \(A = 13\).

4. Isotopes are atoms of the same element that differ in the number of neutrons present in the nuclei. Since the number of protons is the same in each such nucleus (the atoms are of the same element), isotopes have the same atomic number \(Z\). Since the number of neutrons present differs between the nuclei, the mass numbers of the nuclei \(A\) are different. Isotopes are atoms of the same element that differ in mass. For example, \(^{13}\text{C}\) and \(^{14}\text{C}\) both represent carbon atoms. However, \(^{13}\text{C}\) has one less neutron than does \(^{14}\text{C}\).

5. The atomic number \(Z\) is written in such formulas as a left subscript, while the mass number \(A\) is written as a left superscript. That is, the general symbol for a nuclide is \(^{A}\text{X}\). As an example, consider the isotope of oxygen with 8 protons and 8 neutrons: its symbol would be \(^{16}\text{O}\).

6. When a nucleus produces an alpha (\(\alpha\)) particle, the atomic number of the nucleus decreases by two units.

7. When a nucleus produces a beta (\(\beta\)) particle, the atomic number of the parent nucleus is increased by one unit. The beta particle has a mass number of zero, but an “atomic number” of \(-1\).

8. Gamma rays are high-energy photons of electromagnetic radiation. Gamma rays are not considered to be particles. When a nucleus produces only gamma radiation, the atomic number and mass number of the nucleus do not change. Gamma rays represent the energy changes associated with transitions and rearrangement of the particles within the nucleus.

9. A positron is a particle with the same mass as an electron, but with the opposite charge: a positron is positively charged. Its mass number is therefore zero, and its “atomic number” is \(+1\). When an unstable nucleus produces a positron, the mass number of the original nucleus is unchanged, but the atomic number of the original nucleus decreases by one unit.

10. Electron capture occurs when one of the inner orbital electrons is pulled into and becomes part of the nucleus.
11. 
\[ ^{12}_{24} \text{Mg} \] (12 protons, 12 neutrons)  
\[ ^{12}_{25} \text{Mg} \] (12 protons, 13 neutrons)  
\[ ^{12}_{26} \text{Mg} \] (12 protons, 14 neutrons)

12.  
a. \[ ^{192}_{83} \text{Bi} \]  
b. \[ ^{204}_{82} \text{Pb} \]  
c. \[ ^{206}_{84} \text{Po} \]

13.  
a. \[ ^{0}_{-1} \text{e} \]  
b. \[ ^{0}_{-1} \text{e} \]  
c. \[ ^{210}_{83} \text{Bi} \]

14.  
a. \[ ^{136}_{53} \text{I} \rightarrow ^{136}_{54} \text{Xe} + ^{0}_{-1} \text{e} \]  
b. \[ ^{133}_{51} \text{Sb} \rightarrow ^{133}_{52} \text{Te} + ^{0}_{-1} \text{e} \]  
c. \[ ^{117}_{49} \text{I} \rightarrow ^{117}_{50} \text{Sn} + ^{0}_{-1} \text{e} \]

15.  
a. \[ ^{226}_{88} \text{Ra} \rightarrow ^{222}_{86} \text{Rn} + ^{4}_{2} \text{He} \]  
b. \[ ^{222}_{86} \text{Rn} \rightarrow ^{218}_{84} \text{Po} + ^{4}_{2} \text{He} \]  
c. \[ ^{239}_{94} \text{Pu} \rightarrow ^{235}_{92} \text{U} + ^{4}_{2} \text{He} \]  
d. \[ ^{4}_{8} \text{Be} \rightarrow ^{2}_{2} \text{He} + ^{2}_{2} \text{He} \]

16. A nuclear transformation represents the change of one element into another. Nuclear transformations are generally accomplished by bombardment of a target nucleus with some small, energetic particle that effects the desired transformation of the target nucleus.

17. There is often considerable repulsion between the target nucleus and the particles being used for bombardment (especially if the bombarding particle is positively charged like the target nucleus). Using accelerators to greatly speed up the bombarding particles can overcome this repulsion.

18. The elements with atomic number greater than 92 are referred to as the transuranium elements. The transuranium elements have been prepared by bombardment reactions of other nuclei.

19. \[ ^{27}_{13} \text{Al} + ^{4}_{2} \text{He} \rightarrow ^{30}_{15} \text{P} + ^{1}_{0} \text{n} \]

20. The probe of a Geiger (Geiger-Müller) counter contains argon gas. The argon atoms themselves have no charge, but they can be ionized by high-energy particles from a radioactive decay process. Although a sample of normal uncharged argon gas does not
conduct an electric current, argon gas that has been ionized will briefly conduct an electric current (until the argon ions and electrons recombine). If an electric field is applied to the argon gas probe, then a brief pulse of electricity will be passed through the argon every time an ionization event occurs (every time a high-energy particle strikes the argon gas probe). The Geiger counter detects each pulse of current, and these pulses are then counted and displayed on the meter of the device. A scintillation counter uses a substance like sodium iodide, which emits light when struck by a high-energy particle from a radioactive decay. A detector senses the flashes of light from the sodium iodide, and these flashes are then counted and displayed on the meter of the device.

21. The half-life of a nucleus is the time required for one-half of the original sample of nuclei to decay. A given isotope of an element always has the same half-life, although different isotopes of the same element may have greatly different half-lives. Nuclei of different elements typically have different half-lives.

22. When we say that one nucleus is “hotter” than another, we mean that the “hot” nucleus undergoes more decay events per time period. The “hotness” of radionuclei is most commonly indicated by their half-lives (the amount of time required for half a sample to undergo the decay process). A nucleus with a short half-life will undergo more decay events in a given time than a nucleus with a long half-life.

23. highest lowest
\[^{24}\text{Na} > ^{131}\text{I} > ^{60}\text{Co} > ^{3}\text{H} > ^{14}\text{C}\]

24. highest activity lowest activity
\[^{87}\text{Sr} > ^{99}\text{Tc} > ^{24}\text{Na} > ^{99}\text{Mo} > ^{133}\text{Xe} > ^{131}\text{I} > ^{32}\text{P} > ^{51}\text{Cr} > ^{59}\text{Fe}\]

25. For \(^{223}\text{Ra}\), the half-life is 12 days. After two half-lives (24 days), 250 mg remains; after three half-lives (36 days), 125 mg remains.

For \(^{224}\text{Ra}\), the half-life is 3.6 days. One month would be approximately 8 half-life periods (29 days), and approximately 4 mg remains.

For \(^{225}\text{Ra}\), the half-life is 15 days. One month would be two half-life periods, and 250 mg remains.

26. For an administered dose of 100 \(\mu\text{g}\), 0.39 \(\mu\text{g}\) remains after 2 days. The fraction remaining is 0.39/100 = 0.0039; on a percentage basis, less than 0.4% of the original radioisotope remains.

27. Carbon-14 (\(^{14}\text{C}\)) is most commonly used in the radiodating of archaeological artifacts.

28. Carbon-14 is produced in the upper atmosphere by the bombardment of ordinary nitrogen with neutrons from space:
\[^{14}\text{N} + ^{1}\text{n} \rightarrow ^{14}\text{C} + ^{1}\text{H}\]
29. The quantity of $^{14}_{6}\text{C}$ in the atmosphere is assumed to remain constant because a balance exists between the continued production of $^{14}_{6}\text{C}$ from bombardment of nitrogen in the upper atmosphere by cosmic rays, and the decay of $^{14}_{6}\text{C}$ through beta particle production.

30. We assume that the concentration of C-14 in the atmosphere is effectively constant. A living organism is constantly replenishing C-14 through the processes of either metabolism (sugars ingested in foods contain C-14) or photosynthesis (carbon dioxide contains C-14). When a plant dies, it no longer replenishes itself with C-14 from the atmosphere, and as the C-14 undergoes radioactive decay, its amount decreases with time.

31. A radiotracer is a radioactive nuclide that can be introduced into an organism in food or drugs, whose pathway through the body can then be traced by monitoring of the radioactivity of the nuclide. Carbon-14 and phosphorus-32 have been used to study the conversion of nutrients into energy by living cells.

32. These isotopes and their uses are listed in Table 19.4. Some important examples include the use of I-131 (and other iodine isotopes) in the diagnosis and treatment of thyroid disease (iodine is used in the body primarily in the thyroid gland); Fe-59 in the study of the function of red blood cells (iron is a constituent of hemoglobin, which is found in the red blood cells); and Sr-87 in the study of bones (Sr is a Group 2 element, and is able to take the place of Ca in bone structures).

33. The forces that hold protons and neutrons together in the nucleus are much greater than the forces that bind atoms together in molecules.

34. Combining two light nuclei to form a heavier, more stable nucleus is called nuclear fusion. Splitting a heavy nucleus into nuclei with smaller mass numbers is called nuclear fission.

35. The energies released by nuclear processes are on the order of $10^6$ times more powerful than those associated with ordinary chemical reactions.

36. $^0_1\text{n} + ^{235}_{92}\text{U} \rightarrow ^{142}_{56}\text{Ba} + ^{89}_{36}\text{Kr} + 3^0_1\text{n}$ is one possibility.

37. The fission of $^{235}_{92}\text{U}$ is initiated by bombardment of the nucleus with neutrons from an outside source. For every nucleus of $^{235}_{92}\text{U}$ that decays, however, three neutrons are produced by the process. Once the reaction has been started with neutrons from an outside source, the neutrons generated by the reaction itself can go on to cause other nuclei of $^{235}_{92}\text{U}$ to decay, thereby producing still more neutrons, and so on. All that is needed to sustain such a chain reaction is a sufficient density of $^{235}_{92}\text{U}$, so that the emitted neutrons are not lost to the outside.

38. A critical mass of a fissionable material is the amount needed to provide a high enough internal neutron flux to sustain the chain reaction (enough neutrons are produced to cause the continuous fission of further material). A sample with less than a critical mass is still radioactive, but cannot sustain a chain reaction.
39. The moderator in a uranium fission reactor surrounds the fuel rods and slows down the neutrons produced by the uranium decay process so that they can be absorbed more easily by other uranium atoms. The control rods are constructed of substances that absorb neutrons, and can be inserted into the reactor core to control the power level of the reactor. The containment of a reactor refers to the building in which the reactor core is located, which is designed to contain the radioactive core in the event of a nuclear accident. A cooling liquid (usually water) is circulated through the reactor to draw off the heat energy produced by the nuclear reaction, so that this heat energy can be converted to electrical energy in the power plant’s turbines.

40. An actual nuclear explosion, of the type produced by a nuclear weapon, cannot occur in a nuclear reactor because the concentration of the fissionable materials is not sufficient to form a supercritical mass. However, since many reactors are cooled by water, which can decompose into hydrogen and oxygen gases, a chemical explosion is possible, which could scatter the radioactive material used in the reactor.

41. If the system used to cool a reactor core fails, the reactor may reach temperatures high enough to melt the core itself. In a scenario referred to as the “China Syndrome,” the molten reactor core could become hot enough so as to melt through the bottom of the reactor building and into the earth itself (eventually the molten material would reach cool ground water and resolidify, with possible release of radioactivity). If water is used to cool the reactor core, and the cooling system becomes blocked, it is possible for the heat from the reactor to cause a steam explosion (which would also release radioactivity), or to break down the coolant water into hydrogen gas (which could also explode).

42. \[ ^{238}_{92}U + _0^1n \rightarrow ^{239}_{92}U \]
   \[ ^{239}_{92}U \rightarrow ^{239}_{93}Np + \_0^1e \]
   \[ ^{239}_{93}Np \rightarrow ^{239}_{94}Pu + \_0^1e \]

43. Nuclear fusion is the process of combining two light nuclei into a larger nucleus, with an energy release larger even than that provided by fission processes.

44. In one type of fusion reactor, two \(^1\)\(^2\)H atoms are fused to produce \(^4\)\(^2\)He. Because the hydrogen nuclei are positively charged, extremely high energies (temperatures of 40 million K) are needed to overcome the repulsion between the nuclei as they are shot into each other.

45. Fusion produces an enormous amount of energy per gram of fused material. If it is hydrogen that is to be fused, the earth possesses an enormous supply of the needed raw materials in the oceans; the product nuclei from the fusion of hydrogen (helium isotopes) are far less dangerous than those produced by fission processes.

46. Although the energy transferred per event to a living creature is small, the quantity of energy is enough to break chemical bonds, which may cause malfunctioning of cellular systems. In particular, many biochemical processes are chain-like in nature, and the production of a single odd ion in a cell by a radioactive event may have a cumulative effect. For example, ionization of a single bond in a sex cell may cause a drastic mutation in the creature resulting.
47. Somatic damage is damage directly to the organism itself, causing nearly immediate sickness or death to the organism. Genetic damage is damage to the genetic machinery of the organism, which will be manifested in future generations of offspring.

48. Alpha particles are stopped by the outermost layers of skin; beta particles penetrate only about 1 cm into the body; gamma rays are deeply penetrating.

49. Gamma rays penetrate long distances, but seldom cause ionization of biological molecules. Alpha particles, because they are much heavier although less penetrating, are very effective at ionizing biological molecules and leave a dense trail of damage in the organism. Isotopes that release alpha particles can be ingested or breathed into the body where the damage from the alpha particles will be more acute.

50. Nuclei of atoms that are chemically inert, or which are not ordinarily found in the body, tend to be excreted from the body quickly and do little damage. Other nuclei of atoms that form a part of the body’s structure or normal metabolic processes are likely to be incorporated into the body. When a radioactive nuclide is ingested into the body, its capacity to cause damage also depends on how long it remains in the body. If the nuclide has been incorporated into the body, the danger is greatest.

51. The exposure limits given in Table 19.5 as causing no detectable clinical effect are 0–25 rem. The total yearly exposures from natural and human-induced radioactive sources are estimated in Table 19.6 as less than 200 millirem (0.2 rem), which is well within the acceptable limits.

52. The decay series, in order from the top right of the diagram, is:
alpha, beta, beta, alpha, alpha, alpha, alpha, alpha, beta, beta, alpha, beta, beta, alpha. This decay is indicated in color in the figure.

53. a. cobalt is a component of vitamin B\textsubscript{12}
b. bones consist partly of Ca\textsubscript{3}(PO\textsubscript{4})\textsubscript{2}
c. red blood cells contain hemoglobin, an iron–protein compound
d. mercury is absorbed by substances in the brain (this is part of the reason mercury is so hazardous in the environment)

54. Despite the fact that nuclear waste has been generated for over 40 years, no permanent disposal plan has been implemented as yet. One proposal to dispose of such waste calls for the waste to be sealed in blocks of glass, which in turn are sealed in corrosion-proof metal drums, which would then be buried in deep, stable rock formations away from earthquake and other geologically active zones. In these deep storage areas, it is hoped that the waste could decay safely undisturbed until the radioactivity drops to “safe” levels.

55. $^{27}_{13}$Al: 13 protons, 14 neutrons
$^{28}_{13}$Al: 13 protons, 15 neutrons
$^{29}_{13}$Al: 13 protons, 16 neutrons
56. $^{131}$I is used in the diagnosis and treatment of thyroid cancer and other dysfunctions of the thyroid gland. The thyroid gland is the only place in the human body that uses and stores iodine. I-131 that is administered concentrates in the thyroid, and can be used to cause an image on a scanner or x-ray film, or in higher doses, to selectively kill cancer cells in the thyroid. $^{201}$Tl concentrates in healthy muscle cells when administered, and can be used to detect and assess damage to heart muscles after a heart attack: the damaged muscles show a lower uptake of Tl-201 than normal muscles.

57. Breeder reactors are set up to convert nonfissionable $^{238}$U into fissionable $^{239}$Pu. The material used for fission in a breeder reactor is a combination of U-235 (which undergoes fission in a chain reaction) and the more common U-238 isotope. Excess neutrons from the U-235 fission are absorbed by the U-238, converting it to the fissionable plutonium isotope Pu-239. Although Pu-239 is fissionable, its chemical and physical properties make it very difficult and expensive to handle and process.