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**21.2: Nuclear Structure and Stability**

**Q21.2.1**

Write the following isotopes in hyphenated form (e.g., "carbon-14")

a. $^{24}_{11}$Na
b. $^{29}_{13}$Al
c. $^{73}_{36}$Kr
d. $^{194}_{77}$Ir

**S21.2.1**

Isotopes are named by the element followed by the molecular weight.

1. The element is Sodium and this isotope has a molecular weight of 24. Therefore, this isotope is named Sodium-24.

2. The element is Aluminum and this isotope has a molecular weight of 29. Therefore, this isotope is named Aluminum-29.

3. This element is Kryton and this isotope has a molecular weight of 73. Therefore, this isotope is named Kryton-73.

4. This element is Iridium and this isotope has a molecular weight of 194. Therefore, this isotope is named Iridium-194.

**A21.2.1**

(a) sodium-24; (b) aluminum-29; (c) krypton-73; (d) iridium-194

**Q21.2.2**

Write the following isotopes in nuclide notation (e.g., "$^{14}_6C$")

a. oxygen-14
To understand the question, we need to go over what a nuclide is. A nuclide is a specific type of atom/nucleus that is determined by the number of protons and neutrons. Each has a chemical element symbol. The atomic number \((Z)\) symbolizes the number of protons in the nucleus, and the mass number \((A)\) is the total number of protons and neutrons in the nucleus. If you wanted find the number of neutrons you would subtract \(Z-A\).

So it would be like \(_{8}^{16}\text{O}\) for oxygen. 16 being A and 8 being Z.

Apply this to these questions.

1. Oxygen has a mass number of 14. Go to the periodic table and find the atomic number, which is 8. The format would be \(_{8}^{14}\text{O}\)

2. Copper has a mass number of 70. Go to the periodic table and find the atomic number, which is 29. The format would be \(_{29}^{70}\text{Cu}\)

3. Tantalum has a mass number of 175. Go to the periodic table and find the atomic number, which is 73. The format would be \(_{73}^{175}\text{Ta}\)

4. Francium has a mass number of 217. Go to the periodic table and find the atomic number, which is 87. The format would be \(_{87}^{217}\text{Fr}\)

For the following isotopes that have missing information, fill in the missing information to complete the notation

a. \(_{14}^{34}\text{X}\)

b. \(_{56}^{36}\text{P}\)

c. \(_{57}^{57}\text{X}\text{Mn}\)

d. \(_{56}^{121}\text{X}\text{X}\)
Standard notation for elements and their isotopes are as follows:

\[ ^{A}_{Z}X \]

Where \( Z \) corresponds to the atomic number (number of protons), \( A \) corresponds to the atomic mass number (total number of protons and neutrons), and \( X \) corresponds to the letters assigned to our given element. It's important to remember that an element can have a number of isotopes with varying numbers of neutrons, however the atomic number (number of protons) is unique for each and every element and will dictate its identity.

a. \( ^{34}_{14}Si \) - The atomic (proton) number (lower number) dictates the identity of the element. In this case, an atomic number of 14 corresponds to silicon.

b. \( ^{36}_{15}P \) - Again, each element has its own unique atomic number. The atomic number for phosphorus is 15.

c. \( ^{57}_{25}Mn \) - Looking at the periodic table, the atomic number for Mn is 25.

d. \( ^{121}_{56}Ba \) - Finally, an atomic number of 56 corresponds to barium according to the periodic table.

For each of the isotopes in Question 21.2.3, determine the numbers of protons, neutrons, and electrons in a neutral atom of the isotope.

a) The total number of proton is 14. The total number of neutron is 20 because the neutrons number= mass number-proton number. And the electron number is 14 because electron number equals to proton number.

b)Since the element is P we can find its proton number at the periodic table, which is 15. Since neutrons number= mass number-proton number, so 36-15=21, so neutron number is 21. And electron number is 15 because electron number equals to proton number.

c)Since the element is Mn we can find its proton number at the periodic table, which is 25. Since neutrons number= mass number-proton number, so 57-25=32, so neutron number is 32. And electron number is 25 because electron number equals to proton number.

d)The proton number is 56 which is given in the question. Since neutrons number= mass number-proton number, so 121-56=65, so neutron number is 65. And electron number is 56 because electron number equals to proton number.
A21.2.4

a) protons=electrons=14; neutrons= 20
b) protons=electrons=15; neutrons= 21
c) protons=electrons=25; neutrons= 32
d) protons=electrons=56; neutrons= 65

Q21.2.5

Write the nuclide notation, including charge if applicable, for atoms with the following characteristics:

- a. 25 protons, 20 neutrons, 24 electrons
- b. 45 protons, 24 neutrons, 43 electrons
- c. 53 protons, 89 neutrons, 54 electrons
- d. 97 protons, 146 neutrons, 97 electrons

S21.2.5

\[ ^{A}_{Z} \text{Element}^{\text{Charge}} \tag{1} \]

\[ \text{A} = Z + N \tag{2} \]

\[ \text{Charge} = Z - E \tag{3} \]

In the above equations, A is the mass number, Z is the proton number, N is the neutron number, and E is the number of electrons.

1. From the given information:

\[ (Z = 25), (N = 20), (E = 24) \]

Mass number is 45, obtained when summing number of protons and neutrons.

\[ (A = 25 + 20 = 45) \]

This particular atom has a +1 charge because there is one more proton than electron.

\[ (\text{Charge} = 25 - 24 = 1) \]

Using the periodic table of elements, we see that an element with 25 protons corresponds to Manganese (Mn). Finally, plug in A, Z, Charge, and the corresponding element symbol into Equation 1.
2. From the given information:

\( Z = 45 \), \( N = 24 \), \( E = 43 \)

Mass number is 69, obtained when summing number of protons and electrons.

\( A = 45 + 24 = 69 \)

This particular atom has a +2 charge because there are two more protons than electrons.

\( \text{Charge} = 45 - 43 = 2 \)

An element with 45 protons corresponds to Rhodium (Rh). Finally, plug in \( A \), \( Z \), \( \text{Charge} \), and the corresponding element symbol into Equation 1.

\( ^{69}_{45}\text{Rh}^{+2} \)

3. From the given information:

\( Z = 53 \), \( N = 89 \), \( E = 54 \)

Mass number is 142, obtained when summing number of protons and electrons.

\( A = 53 + 89 = 142 \)

This particular atom has a -1 charge because there are two more protons than electrons.

\( \text{Charge} = 53 - 54 = -1 \)

An element with 53 protons corresponds to Iodide (I). Finally, plug in \( A \), \( Z \), \( \text{Charge} \), and the corresponding element symbol into Equation 1.

\( ^{142}_{53}\text{I}^{-1} \)

4. From the given information:

\( Z = 97 \), \( N = 146 \), \( E = 97 \)

Mass number is 247, obtained when summing number of protons and neutrons.

\( A = 97 + 146 = 243 \)
This particular atom has a neutral charge because there is a proton for every neutron.

\[ \text{Charge} = 97 - 97 = 0 \]

An element with 97 protons is Berkelium (Bk). Finally, plug in A, Z, Charge, and the corresponding element symbol into Equation 1.

\[ \ce{^{243}_{97}Bk} \]

S21.2.5

a. \(\ce{^{45}_{25}Mn^{+1}}\);

b. \(\ce{^{69}_{45}Rh^{+2}}\);

c. \(\ce{^{142}_{53}I^{-1}}\);

d. \(\ce{^{243}_{97}Bk}\)

Q21.2.6

Calculate the density of the \(\ce{^{24}_{12}Mg}\) nucleus in g/mL, assuming that it has the typical nuclear diameter of \(1 \times 10^{-13}\) cm and is spherical in shape.

Figure out how many protons and neutrons there are in \(\ce{^{24}_{12}Mg}\). Since atomic number of \(Mg\) is 12, it has 12 protons. To find the neutrons, subtract the atomic number 12 from the mass number, which is 24.

\[24 - 12 = 12\]

So \(\ce{^{24}_{12}Mg}\) has 12 protons and 12 neutrons. Now find the mass of the \(\ce{^{24}_{12}Mg}\) nucleus in grams, where \(m_{\text{proton}}=1.6726219\times10^{-24}\text{g}\) and \(m_{\text{neutron}}=1.6749286\times10^{-24}\text{g}\).

Alternatively, you can use atomic mass units, with \(m_{\text{proton}}=1.007825\text{u}\), \(m_{\text{neutron}}=1.008665\text{u}\), and the conversion \((\frac{1.6605\times10^{-24}\text{g}}{1\text{u}})\).

\[m=12(1.6726219\times10^{-24}\text{g})+12(1.6749286\times10^{-24}\text{g})=4.0170606\times10^{-23}\text{g}\]

The volume is assumed to be "spherical in shape" and the nuclear diameter given to be \((1\times10^{-13}\text{cm})\). Using the equation for the volume of a sphere, with \(r=(\frac{1}{2}\times10^{-13}\text{cm})\) (the radius is half the diameter), find the volume.

\[V=\frac{\pi}{6}\times10^{-40}\text{cm}^3\]

Since our answer must be in \(g/mL\), use the conversion \((\frac{1\text{cm}^3}{1\text{mL}})\) to convert cubic centimeters to milliliters.
\[ V = (5.24 \times 10^{-40} \text{cm}^3) \left( \frac{1 \text{mL}}{1 \text{cm}^3} \right) = 5.24 \times 10^{-40} \text{mL} \]

Density is mass divided by volume.

\[ d = \frac{m}{V} = \frac{4.0170606 \times 10^{-23} \text{g}}{5.24 \times 10^{-40} \text{mL}} = 7.67 \times 10^{16} \text{g/mL} \]

This is extremely dense! Which shows the majority of the universe is essentially empty space.

**A21.2.6**

\[ 7.67 \times 10^{16} \text{g/mL} \]

**Q21.2.7**

What are the two principal differences between nuclear reactions and ordinary chemical changes?

**S21.2.7**

- The first principal difference between nuclear reactions and ordinary chemical changes is how the reaction takes place in the atom. Nuclear reaction happens in the atom's nucleus and involves the splitting of the nuclei which makes the element unstable and emitting neutrons/protons. It results in radiation (alpha, beta, or gamma) in order to come back to stability. On the other hand, chemical reaction happens outside the nucleus and involves the two atoms' electrons where they are rearrange (transfer and share of electrons) in order for atoms to gain stability.

- The second principal difference between nuclear and chemical reactions is their energy change. Nuclear reaction involves high energy change, while chemical reaction only involves low energy change. In nuclear reaction, a tiny difference from the product's total mass and reactant’s total mass can produce a massive amount of energy release.

**A21.2.7**

Nuclear reactions usually change one type of nucleus into another; chemical changes rearrange atoms. Nuclear reactions involve much larger energies than chemical reactions and have measurable mass changes.

**Q21.2.8**

The mass of the atom \( \text{^{23}Na} \) is 22.9898 amu.

a. Calculate its binding energy per atom in millions of electron volts.
b. Calculate its binding energy per nucleon.

\[ \text{Δm} = 0.200 \text{amu} \]

Then convert amu to kg.

\[ 0.200 \text{amu} \times \frac{1.661 \times 10^{-27} \text{ kg}}{1 \text{ amu}} = 3.325 \times 10^{-28} \text{ kg} \]

Then plug in \( m \) into \( E=mc^2 \) to find \( E \), where \( c = 3.00 \times 10^8 \text{ m/s} \)

\[ E = 3.325 \times 10^{-28} \text{J} \times (3.00 \times 10^8)^2 = 2.99 \times 10^{-11} \text{J(atom)} \]

Because the answer above is in J and we want our answer in meV, we have to do the conversion to get to millions of electron volts

\[ 2.99 \times 10^{-11} \text{J} \times \frac{1 \text{ meV}}{1.602 \times 10^{-13} \text{J}} = 186.64 \text{meV} \]

b. To calculate the binding energy per nucleon, take the calculated answer from part a, 186.64 meV and divide it by the number of nucleons which is 23 in this case (12 neutrons + 11 protons)

\[ 186.64 \text{meV} / 23 = 8.11 \text{meV per nucleon} \]

A21.2.8

a) 186.64 meV
Which of the following nuclei lie within the band of stability?

a. chlorine-37
b. calcium-40
c. $^{204}$Bi
d. $^{56}$Fe
e. $^{206}$Pb
f. $^{211}$Pb
g. $^{222}$Rn
h. carbon-14

Figure 21.2.9: The Relationship between Nuclear Stability and the Neutron-to-Proton Ratio.
Most elements have isotopes. For stable isotopes, a plot referred to as the Nuclear Belt of Stability shows a ratio of neutrons to protons that will deem the isotope stable.

a) Isotopes with atomic number \((Z) \leq 20\) and with a neutron \((n)\) to proton \((p)\) ratio of about 1 are more likely to be stable

b) Isotopes with atomic number \((Z) < 82\), have one or more stable isotopes with exceptions being technetium \((Z = 43)\) and promethium \((Z = 61)\) which do not have any stable isotopes

   i) even number of protons and even numbers of neutrons is most likely to be stable

   ii) odd numbers of protons and odd numbers of neutrons is most likely to be unstable

   iii) limit of 209 nucleons in stable nucleus

c) Isotopes with atomic number \((Z) > 83\) are unstable

Looking at the graph:

1. chlorine-37; \(p = 17, n = 20\), stable (within band of stability)
2. calcium-40; \(p = 20, n = 20\), stable (within band of stability)
3. \(^{204}\text{Bi}\); \(p = 83, n = 121\), stable (within band of stability and under the limit of max nucleons)
4. \(^{56}\text{Fe}\); \(p = 26, n = 30\), stable (within band of stability)
5. \(^{206}\text{Pb}\); \(p = 82, n = 124\), stable (within band of stability)
6. \(^{211}\text{Pb}\); \(p = 82, n = 129\), unstable, radioactive (above band of stability)
7. \(^{222}\text{Rn}\); \(p = 86, n = 136\), unstable, radioactive (above band of stability and atomic number > 82)
8. carbon-14; \(p = 12, n = 2\), unstable, radioactive (below band of stability and ratio way below 1)

A21.2.9

(a), (b), (c), (d), and (e)

Q21.2.10

Which of the following nuclei lie within the band of stability?

a. argon-40
b. oxygen-16
c. \(^{122}\text{Ba}\)
d. \(^{58}\text{Ni}\)
e. \(^{205}\text{TI}\)
f. \(^{210}\text{TI}\)
g. \(^{226}\text{Ra}\)
In this problem, we have to determine whether each of these nuclear isotopes lies within the band of stability. The stability of a nucleus depends on:

1. the neutron:proton ratio of the isotope.
2. the amount of nucleons (neutrons and protons) in the nucleus.

Furthermore, there are also some rules that help determine the stability of a nucleus:

1. Nuclei are generally (but not always) stable if the number of nucleons is an even number.
2. Specific numbers of protons or neutrons are stable (magic numbers):
   
   2, 8, 20, 28, 50, 82, 114 (protons), 126 (neutrons), 184 (neutrons)

The neutron:proton ratio that determines if an isotope is stable depends on the atomic number of the isotope. The ratios are:

- 1:1 if the atomic number < 20
- 1.5:1 if the atomic number is 20-83
- nonexistent for atomic number > 83 because all isotopes after this atomic number are unstable

a) argon-40

#neutrons: 22 #protons: 18 #nucleons: 40

**Stable** because the number of nucleons are even.

b) oxygen-16

#neutrons: 8 #protons: 8 #nucleons: 16

**Stable** because the neutron:proton ratio is 1:1 and the atomic number is less than 20.

c) $^{122}_{56}$Ba

#neutrons: 66 #protons: 56 #nucleons: 122

**Unstable** because the neutron:proton ratio is 66:56, which is equal to 1.18:1 and atomic number is between 20 and 83.

d) $^{55}_{28}$Ni

#neutrons: 30 #protons: 28 #nucleons: 58

**Stable** because the number of protons is 28, which is a magic number.
e) $^{205}$Tl

#neutrons: 124 #protons: 81 #nucleons: 205

**Stable** because the neutron:proton ratio is 124:81, which is equal to 1.53:1 and the atomic number is between 20 and 83.

f) $^{210}$Tl

#neutrons: 129 #protons: 81 #nucleons: 210

**Unstable** because number of both neutrons and protons are odd.

g) $^{226}$Ra

**Unstable** because the atomic number of radon is 88, which is greater than 83.

h) magnesium-24

#neutrons: 12 #protons: 12 #nucleons: 24

**Stable** because the neutron:proton ratio is 1:1 and the atomic number is less than 20.

Therefore isotopes a, b, d, e, and h lie within the band of stability.

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### 21.3: Nuclear Equations

**Q21.3.1**

Write a brief description or definition of each of the following:

a. nucleon  
b. α particle  
c. β particle  
d. positron  
e. γ ray  
f. nuclide  
g. mass number  
h. atomic number

**S21.3.1**

1. Nucleons are made up of two important subatomic particles: protons and neutrons, which are the particles within the nucleus.
2. α particles are made up of two protons and two neutrons like the nucleus of a helium particle (ie. \(_{2}^{4}\text{He}\)). They are produced through a radioactive process called alpha decay.

3. β particles are high energy and high speed electrons with a mass of zero and a charge of -1 (ie. \(_{-1}^{0}\text{e}\)). They are produced through a radioactive process called beta decay.

4. Positrons have the same mass of an electron, but instead of a negative charge, they have a positive charge (ie. \(_{1}^{0}\text{e}\)). They are emitted during beta decay.

5. Gamma rays are a form of electromagnetic radiation and they have the smallest wavelength as well as the highest energy.

6. Nuclide refers to a specific number of protons and neutrons in the nucleus.

7. The mass number refers to the sum of the protons and the neutrons in an element.

8. The atomic number refers to the number of protons in the nucleus of an element.

Q21.3.2

Which of the various particles (α particles, β particles, and so on) that may be produced in a nuclear reaction are actually nuclei?

S21.3.2

α particle is a Helium atom with +2 charge:

\[\alpha : ^4_2\text{He}\]

There are two types of β particles: β⁻ and β⁺.

\[\beta^- : ^0_{-1}\text{e}\]

\[\beta^+: ^0_1\text{e}\]

Gamma:

\[\gamma: ^0_0\text{\gamma}\]

Neutron:

\[^{1}_0\text{n}\]

Since only α particle has both protons and neutrons (2 protons, 2 neutrons), α particle is the only actual nuclei.
Q21.3.3
Complete each of the following equations by adding the missing species:

a. \(\ce{^{27}_{13}Al + ^4_2He? + ^1_0n}\)
b. \(\ce{^{239}_{94}Pu + ? + ^{242}_{96}Cm + ^1_0n}\)
c. \(\ce{^{14}_7N + ^4_2He? + ^1_1H}\)
d. \(\ce{^{235}_{92}U? + ^{135}_{55}Cs + 4^1_0n}\)

S21.3.3

a. \(\ce{^{27}_{13}Al + ^4_2He? ^{30}_{15}P + ^1_0n}\);
b. \(\ce{Pu + He^2 ? ^{242}_{96}Cm + ^1_0n}\);
c. \(\ce{^{14}_7N + ^4_2He? ^{17}_8O + ^1_1H}\);
d. \(\ce{^{235}_{92}U? + ^{135}_{55}Cs + 4^1_0n}\)

Q21.3.4
Complete each of the following equations:

a. \(\ce{^7_3Li + ? + 2^4_2He}\)
b. \(\ce{^{14}_6C? ^{14}_7N + ?}\)
c. \(\ce{^{27}_{13}Al + ^4_2He? + ^1_0n}\)
d. \(\ce{^{250}_{96}Cm ? + ^{98}_{38}Sr + 4^1_0n}\)

Q21.3.5
Write a balanced equation for each of the following nuclear reactions:

a. the production of \(^{17}\text{O}\) from \(^{14}\text{N}\) by \(\alpha\) particle bombardment
b. the production of \(^{14}\text{C}\) from \(^{14}\text{N}\) by neutron bombardment
c. the production of \(^{233}\text{Th}\) from \(^{232}\text{Th}\) by neutron bombardment
d. the production of \(^{239}\text{U}\) from \(^{238}\text{U}\) by \(\ce{^2_1H}\) bombardment

S21.3.5

a. \(\ce{^{14}_6C + He^2 ? ^{17}_8O + ^1_1H}\);
b. \(\ce{^{14}_6C + ^1_0n? ^{14}_6N + ^1_1H}\); (c
c. \(\ce{^{232}_{90}Th + ^1_0n? ^{233}_{90}Th}\); (d
d. \(\ce{^{238}_{92}U + ^2_1H? ^{239}_{92}U + ^1_1H}\)}
Q21.3.6
Technetium-99 is prepared from $^{98}\text{Mo}$. Molybdenum-98 combines with a neutron to give molybdenum-99, an unstable isotope that emits a $\beta$ particle to yield an excited form of technetium-99, represented as $^{99}\text{Tc}^\ast$. This excited nucleus relaxes to the ground state, represented as $^{99}\text{Tc}$, by emitting a $\gamma$ ray. The ground state of $^{99}\text{Tc}$ then emits a $\beta$ particle. Write the equations for each of these nuclear reactions.

Q21.3.7
The mass of the atom $\ce{^{19}_9F}$ is 18.99840 amu.
   a. Calculate its binding energy per atom in millions of electron volts.
   b. Calculate its binding energy per nucleon.

S21.3.7
   a. 148.8 MeV per atom;
   b. 7.808 MeV/nucleon

Q21.3.8
For the reaction $\ce{^{14}_6C + ^{14}_7N \rightarrow \_\_ \_}$, if 100.0 g of carbon reacts, what volume of nitrogen gas (N$_2$) is produced at 273 K and 1 atm?

21.4: Radioactive Decay

Q21.4.1
What are the types of radiation emitted by the nuclei of radioactive elements?

S21.4.1
$\alpha$ (helium nuclei), $\beta$ (electrons), $\beta^+$ (positrons), and $\eta$ (neutrons) may be emitted from a radioactive element, all of which are particles; $\gamma$ rays also may be emitted.

Q21.4.2
What changes occur to the atomic number and mass of a nucleus during each of the following decay scenarios?
   a. an $\alpha$ particle is emitted
   b. a $\beta$ particle is emitted
Q21.4.3
What is the change in the nucleus that results from the following decay scenarios?

a. emission of a β particle
b. emission of a β⁺ particle
c. capture of an electron

c. γ radiation is emitted
d. a positron is emitted
e. an electron is captured

S21.4.3
(a) conversion of a neutron to a proton: \(\ce{^1_0n \rightarrow ^1_1p + ^0_{+1}e}\); (b) conversion of a proton to a neutron; the positron has the same mass as an electron and the same magnitude of positive charge as the electron has negative charge; when the n:p ratio of a nucleus is too low, a proton is converted into a neutron with the emission of a positron: \(\ce{^1_1p \rightarrow ^1_0n + ^0_{+1}e}\); (c) In a proton-rich nucleus, an inner atomic electron can be absorbed. In simplest form, this changes a proton into a neutron: \(\ce{^1_1p + ^0_{-1}e \rightarrow ^1_0p}\)

Q21.4.4
Many nuclides with atomic numbers greater than 83 decay by processes such as electron emission. Explain the observation that the emissions from these unstable nuclides also normally include α particles.

Q21.4.5
Why is electron capture accompanied by the emission of an X-ray?

S21.4.5
The electron pulled into the nucleus was most likely found in the 1s orbital. As an electron falls from a higher energy level to replace it, the difference in the energy of the replacement electron in its two energy levels is given off as an X-ray.

Q21.4.6
Explain how unstable heavy nuclides (atomic number > 83) may decompose to form nuclides of greater stability (a) if they are below the band of stability and (b) if they are above the band of stability.

Q21.4.7
Which of the following nuclei is most likely to decay by positron emission? Explain your choice.

a. chromium-53
b. manganese-51  
c. iron-59

S21.4.7

Manganese-51 is most likely to decay by positron emission. The n:p ratio for Cr-53 is \(\frac{29}{24} = 1.21\); for Mn-51, it is \(\frac{26}{25} = 1.04\); for Fe-59, it is \(\frac{33}{26} = 1.27\). Positron decay occurs when the n:p ratio is low. Mn-51 has the lowest n:p ratio and therefore is most likely to decay by positron emission. Besides, \(\ce{^{53}_{24}Cr}\) is a stable isotope, and \(\ce{^{59}_{26}Fe}\) decays by beta emission.

Q21.4.8

The following nuclei do not lie in the band of stability. How would they be expected to decay? Explain your answer.

  a. \(\ce{^{34}_{15}P}\)  
  b. \(\ce{^{239}_{92}U}\)  
  c. \(\ce{^{38}_{20}Ca}\)  
  d. \(\ce{^3_1H}\)  
  e. \(\ce{^{245}_{94}Pu}\)

Q21.4.9

The following nuclei do not lie in the band of stability. How would they be expected to decay?

  a. \(\ce{^{28}_{15}P}\)  
  b. \(\ce{^{235}_{92}U}\)  
  c. \(\ce{^{37}_{20}Ca}\)  
  d. \(\ce{^9_3Li}\)  
  e. \(\ce{^{245}_{96}Cm}\)

S21.4.9

(a) \(\beta\) decay; (b) \(\alpha\) decay; (c) positron emission; (d) \(\beta\) decay; (e) \(\alpha\) decay

Q21.4.10

Predict by what mode(s) of spontaneous radioactive decay each of the following unstable isotopes might proceed:

  a. \(\ce{^{6}_{2}He}\)  
  b. \(\ce{^{60}_{30}Zn}\)  
  c. \(\ce{^{235}_{91}Pa}\)  
  d. \(\ce{^{241}_{94}Np}\)  
  e. \(\ce{^{18}_{8}F}\)
Q21.4.11

Write a nuclear reaction for each step in the formation of $^{218}_{84}\text{Po}$ from $^{238}_{92}\text{U}$, which proceeds by a series of decay reactions involving the step-wise emission of $\alpha$, $\beta$, $\beta$, $\alpha$, $\alpha$, $\alpha$ particles, in that order.

S21.4.11

$^{238}_{92}\text{U} \rightarrow^{234}_{90}\text{Th} + ^{4}_{2}\text{He}$

$^{234}_{90}\text{Th} \rightarrow^{234}_{91}\text{Pa} + ^{0}_{-1}\text{e}$

$^{234}_{91}\text{Pa} \rightarrow^{234}_{92}\text{U} + ^{0}_{-1}\text{e}$

$^{234}_{92}\text{U} \rightarrow^{230}_{90}\text{Th} + ^{4}_{2}\text{He}$

$^{230}_{90}\text{Th} \rightarrow^{226}_{88}\text{Ra} + ^{4}_{2}\text{He}$

$^{226}_{88}\text{Ra} \rightarrow^{222}_{86}\text{Rn} + ^{4}_{2}\text{He}$

$^{222}_{86}\text{Rn} \rightarrow^{218}_{84}\text{Po} + ^{4}_{2}\text{He}$

Q21.4.12

Write a nuclear reaction for each step in the formation of $^{208}_{82}\text{Pb}$ from $^{228}_{90}\text{Th}$, which proceeds by a series of decay reactions involving the step-wise emission of $\alpha$, $\alpha$, $\alpha$, $\alpha$, $\beta$, $\beta$, $\alpha$ particles, in that order.

Q21.4.13

Define the term half-life and illustrate it with an example.

S21.4.13

Half-life is the time required for half the atoms in a sample to decay. Example (answers may vary): For C-14, the half-life is 5770 years. A 10-g sample of C-14 would contain 5 g of C-14 after 5770 years; a 0.20-g sample of C-14 would contain 0.10 g after 5770 years.

Q21.4.14

A $1.00 \times 10^{-6}$-g sample of nobelium, $^{254}_{102}\text{No}$, has a half-life of 55 seconds after it is formed. What is the percentage of $^{254}_{102}\text{No}$ remaining at the following times?

a. 5.0 min after it forms
b. 1.0 h after it forms

Q21.4.15

\( ^{239}\text{Pu} \) is a nuclear waste byproduct with a half-life of 24,000 y. What fraction of the \( ^{239}\text{Pu} \) present today will be present in 1000 y?

S21.4.15

\( \left( \frac{1}{2} \right)^{0.04} = 0.973 \) or 97.3%

Q21.4.16

The isotope \( ^{208}\text{Tl} \) undergoes \( \beta \) decay with a half-life of 3.1 min.

a. What isotope is produced by the decay?

b. How long will it take for 99.0% of a sample of pure \( ^{208}\text{Tl} \) to decay?

c. What percentage of a sample of pure \( ^{208}\text{Tl} \) remains un-decayed after 1.0 h?

Q21.4.17

If 1.000 g of \( ^{226}\text{Ra} \) produces 0.0001 mL of the gas \( ^{222}\text{Rn} \) at STP (standard temperature and pressure) in 24 h, what is the half-life of \( ^{226}\text{Ra} \) in years?

S21.4.17

Using the equation for first-order kinetics, the following equation can be derived:

\[ \ln \frac{N}{N_0} = -kt \]

where "N" is the amount of radioisotope remaining after time "t" has elapsed. "N_0" is the initial amount of radioisotope at the beginning of the period, and "k" is the rate constant for the radioisotope.

For this problem we are going to use moles for our measure of \( N/N_0 \), however other units of measure, such as grams, work as well as long as the two match.

In this case, we must first calculate the original amount of moles of \( ^{226}\text{Ra} \)

\[ (1.000 \text{ g})(1 \text{ mole } / 226 \text{ g}) = 4.425 \times 10^{-3} \text{ moles } ^{226}\text{Ra} \]

Now we must calculate the amount of moles of \( ^{222}\text{Rn} \) produced in 1 day (24 hours) by calculating the amount of moles of \( ^{222}\text{Rn} \) produced.

\[ (.0001 \text{ mL})(1 \text{ L } / 1000 \text{ mL})(1 \text{ mole } / 22.4 \text{ L } \text{(at STP)}) = 4.46 \times 10^{-9} \text{ moles } ^{222}\text{Rn} \]
So the amount of \(_{88}^{226}\text{Ra}\) remaining can be calculated by

\[
\text{(initial moles }_{88}^{226}\text{Ra}) - \text{(moles }_{86}^{222}\text{Rn} \text{ produced}) = (0.0044247788) - (4.464285714 \times 10^{-9}) = 0.0044247743 \text{ moles remaining}
\]

Now using the values of initial and remaining moles of \(_{88}^{226}\text{Ra}\) in the equation above we can solve for \(k\) getting (1/365 years = 1 day)

\[
\ln \frac{(0.0044247743)}{(0.0044247788)} = -k \left(\frac{1}{365}\right)
\]

\[
k = \frac{(1.017 \times 10^{-6})}{.0027} = 3.71 \times 10^{-4} \text{ years}^{-1}
\]

We can use our calculated value of \(k\) and use the same equation to solve of the half life of \(_{86}^{222}\text{Rn}\)

Since half life infers half of \(_{86}^{222}\text{Rn}\) remains, "\(N/N_0\)" will be 0.5 so

\[
\ln (0.5) = -(3.71 \times 10^{-4})t
\]

\[
t = \frac{(-0.6931471806)}{(-3.71 \times 10^{-4})} = 1868.32 \text{ years}
\]

since there is only 1 significant figure given,

\[
t = 2.00 \times 10^{3} \text{ years}
\]

---

**A21.4.17**

\[2 \times 10^{3} \text{ y}\]

**Q21.4.18**

The isotope \(\text{^{90}_{38}Sr}\) is one of the extremely hazardous species in the residues from nuclear power generation. The strontium in a 0.500-g sample diminishes to 0.393 g in 10.0 y. Calculate the half-life.

**S21.4.18**

Radioactive decay is a first order reaction mechanism.

Therefore half life is independent of the initial concentration.

\[
\text{Half life} = \frac{(\ln 2)}{k}
\]

First calculate the rate constant

\[
A = A_0 e^{-kt}\]

\[
0.393 = 0.500 e^{-10k}
\]
\[
\text{ln}(0.786) = \text{ln}(e^{-10k})
\]
\[
k = \frac{\text{ln}(0.786)}{-10} = 0.024
\]
\[
\text{Half-life} = \frac{\text{ln}(2)}{0.024} = 28.8 \text{ years}
\]

Q21.4.19

Technetium-99 is often used for assessing heart, liver, and lung damage because certain technetium compounds are absorbed by damaged tissues. It has a half-life of 6.0 h. Calculate the rate constant for the decay of \(\ce{^{99}_{43}Tc}\).

S21.4.19

- Remember, the equation for half-life is \(N = N_0 e^{kt}\)
- \(N\) is the final concentration (.5 in this case)
- \(N_0\) is initial concentration
- \(k\) is rate constant
- \(t\) is time (in any unit)

1. \((.5) = 1e^{-k(6)}
2. \text{To bring down the } -kt \text{ and eliminate the } e, \text{ we take the natural log (ln) of both sides}
   - \(\text{ln} (.5) = \text{ln}(e^{-k(6)})
   - \text{ln} (.5) = -k(6)
3. Solve for \(k\)
   - \(k = \text{ln} (.5)/-6\)
   - \(k = .12 \text{ h}^{-1}\)

- It’s always in first order, so it’s 1/unit of time

A21.4.19

0.12 h\(^{-1}\)

Q21.4.20

What is the age of mummified primate skin that contains 8.25% of the original quantity of \(^{14}\text{C}\)?
S21.4.20

Use the half life of carbon-14 to determine \( k \) using the equation: \( t_{1/2} = \frac{\ln(2)}{k} \). We use this equation because radioactive decay is first order.

\[ 5730 \text{ years} = \frac{\ln(2)}{k} \]

\[ k = -1.21 \times 10^{-4} \]

Second, use this constant to calculate the amount of time that has passed using this equation: \( \ln\left(\frac{A_0}{A}\right) = -kt \)

\[ \ln(0.0825) = -1.21 \times 10^{-4} \times t \]

\[ t = 20625 \text{ years} \]

A21.4.20

\[ t = 20625 \]

Q21.4.21

A sample of rock was found to contain 8.23 mg of rubidium-87 and 0.47 mg of strontium-87.

a. Calculate the age of the rock if the half-life of the decay of rubidium by \( \beta \) emission is \( 4.7 \times 10^{10} \) y.

b. If some \( \ce{^{87}_{38}Sr} \) was initially present in the rock, would the rock be younger, older, or the same age as the age calculated in (a)? Explain your answer.

S21.4.21

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\[^{s}\]a)

1) solve for decay constant: \( \lambda = \frac{\ln(2)}{t_{1/2}} \rightarrow \frac{\ln(2)}{4.7 \times 10^{10}} = 1.47 \times 10^{-11} \text{ yr}^{-1} \)

2) One mole of rubidium decomposed per mole of strontium produced.

The initial number of moles of rubidium equals number of moles of radium left added to the number of moles of strontium: \( \frac{8.23 \times 10^{-3} \text{ g}}{87 \text{ g/mol}} + \frac{.47 \times 10^{-3} \text{ g}}{87 \text{ g/mol}} = 9.96 \times 10^{-5} \text{ mol} \)

3) plug in \( 10^{-4} \) years for \( N_0 \), \( 9.46 \times 10^{-5} \) years for \( N_t \), and \( 1.47 \times 10^{-11} \) years\(^{-1} \) for
\[ t = \frac{1}{\lambda} \times \ln \frac{N_t}{N_0} \]

\[ \frac{1}{1.47 \times 10^{-11} \text{yrs}^{-1}} \times \ln \frac{10 \times 10^{-4} \text{ yrs}}{9.46 \times 10^{-5} \text{ yrs}} = 3.8 \times 10^{9} \text{ yrs} \]

b) Since time measured is directly proportional to the amount of strontium, the rock would be younger than the actual calculated age if there was some initial amount of strontium present when the rock was formed.

**A21.4.21**

a. 3.8 billion years;

b. The rock would be younger than the age calculated in part (a).

**Q21.4.22**

A laboratory investigation shows that a sample of uranium ore contains 5.37 mg of \( ^{238}_{92}\text{U} \) and 2.52 mg of \( ^{206}_{82}\text{Pb} \). Calculate the age of the ore. The half-life of \( ^{238}_{92}\text{U} \) is \( 4.5 \times 10^9 \) yr.

**S21.4.22**

A laboratory investigation shows that a sample of uranium ore contains 5.37 mg of \( ^{238}_{92}\text{U} \) and 2.52 mg of \( ^{206}_{82}\text{Pb} \). Calculate the age of the ore. The half-life of \( ^{238}_{92}\text{U} \) is \( 4.5 \times 10^9 \) yr.

- Formula we’re going to use: \( N_{\text{Now}} = N_{\text{Orig}} e^{-\lambda t} \)
  - \( N_{\text{Now}} \) is the number of uranium atoms (or mol) present
    - 5.37 mg of \( ^{238}_{92}\text{U} \) = 0.00537g / 238 g/mol = 2.26 x 10^{-5} mol
  - \( N_{\text{Orig}} \) is the number of uranium atoms (or mol) originally (number of uranium atoms + lead atoms currently)
    - 2.52 mg of \( ^{206}_{82}\text{Pb} \) = 0.00252g / 206 g/mol = 1.22 x 10^{-5} mol
    - Sum of Pb and U = 2.26 x 10^{-5} mol + 1.22 x 10^{-5} mol = 3.48 x 10^{-5} mol
  - \( t \) is the time (wanted)
  - \( \lambda \) is the decay rate of uranium (\( \lambda = \ln(2) / t_{1/2} \)) (\( t_{1/2} = 4.5 \times 10^9 \) yr - given)
    - \( \lambda = \ln(2)/4.5 \times 10^9 = 1.54 \times 10^{-10} \text{ year}^{-1} \)
  - Plug and calculate these numbers into the equation and solve for \( t \)
    - \( \ln(2.26 \times 10^{-5} \text{ mol}/3.48 \times 10^{-5} \text{ mol}) = -1.54 \times 10^{-10} \text{ year}^{-1} \times t \)
    - \( t = 2.8 \times 10^9 \) years

**A21.4.22**

2.8 x 10^9 years
Plutonium was detected in trace amounts in natural uranium deposits by Glenn Seaborg and his associates in 1941. They proposed that the source of this $^{239}$Pu was the capture of neutrons by $^{238}$U nuclei. Why is this plutonium not likely to have been trapped at the time the solar system formed $4.7 \times 10^9$ years ago?

This problem focuses on our knowledge of half-lives. Many naturally forming substances on Earth will slowly decay away through nuclear radiation, forming other more stable elements over time. This is the logic behind the science of Carbon dating to determine the age of certain collectables based on the quantity of C-14 remaining in the item.

This question, however, is asking about the decay of U-238 into Pu-239. With the knowledge that the half-life of Pu-239 is 24,100 years, we can plug values into the following equation.

\[ [A]_t = [A]_0 e^{-kt} \]

By plugging in arbitrary numbers such as 100 and 50 for the quantity of Pu-239 sample remaining after the first half-life (24100) years has elapsed, we can determine the k constant.

\[ 50 = 100e^{-k(24100)} \]

Then through simple algebra, we can determine the variable k;

\[ k = \frac{\ln(2)}{24100} \]

which we can now plug back into the original equation to get;

\[ [A]_t = [A]_0 e^{-\left(\frac{\ln(2)}{24100}\right)t} \]

By plugging in a sample size and the age of the solar system... we can determine if it is possible for there to still be trace amounts of Pu-239 remaining on Earth from the beginning of the solar system.

\[ [A]_{4.7 \times 10^9 \text{ years}} = 100e^{-\left(\frac{\ln(2)}{24100}\right) \times (4.7 \times 10^9 \text{ years})} \]

We can then calculate that the remaining quantity of Pu-239 would be...

\[ [A]_{4.7 \times 10^9 \text{ years}} = 0 \]

Meaning, that it would be impossible for any Pu-239 created from the formation of the Earth to be remaining for the scientists to discover in the 1940's. Consequently, any plutonium now present could not have been formed with the uranium.
\textbf{A21.4.23}

c = 0; This shows that no Pu-239 could remain since the formation of the earth. Consequently, the plutonium now present could not have been formed with the uranium.

\textbf{Q21.4.24}

A \((\text{^7}_4\text{Be})\) atom (mass = 7.0169 amu) decays into a \((\text{^7}_3\text{Li})\) atom (mass = 7.0160 amu) by electron capture. How much energy (in millions of electron volts, MeV) is produced by this reaction?

\textbf{S21.4.24}

Electron capture is when an electron in the inner shell is absorbed into the nucleus. This causes a series of events to occur: a proton is converted into a neutron, a neutrino is emitted, and an electron from the next shell falls into the inner shell which causes an x-ray to be emitted.

This certain reaction has the balanced equation:

\[
\text{^7}_4\text{Be} + \text{^0}_{-1}\text{e} \rightarrow \text{^7}_3\text{Li} + \nu_e
\]

Step 1. Calculate the mass defect \(\Delta m\) = Mass of products - Mass of reactants (Note: neutrinos (\(\nu_e\)) have no charge and have a very very low mass that it is almost massless, so we will not include it in the calculation.)

Mass of reactants: \((\text{^7}_4\text{Be})\) is 7.0169 amu, \((\text{^0}_{-1}\text{e})\) is \(0.549 \times 10^{-4}\) amu

\[
\Delta m = 7.01745 \text{ amu} - 7.0160 \text{ amu}
\]

\[
\Delta m = 0.001449 \text{ amu}
\]

Step 2. Convert amu into kg.

\[
0.001449 \text{ amu} \times \frac{1.66 \times 10^{-27} \text{ kg}}{1 \text{ amu}} = 2.4046 \times 10^{-30} \text{ kg}
\]

Step 3. Plug values into famous equation: \(E = mc^2\);

\[
E = (2.4046 \times 10^{-30} \text{ kg}) (2.998 \times 10^8 \text{ m/s})^2
\]

\[
E = 2.1613 \times 10^{-13} \text{ J}
\]

Step 4. Convert J into MeV

\[
2.1613 \times 10^{-13} \text{ J} = 0.00000000000021613 \text{ MeV}
\]
\[
2.1613 \times 10^{-13} \, \text{J} \times \frac{1 \, \text{MeV}}{1.602 \times 10^{-13} \, \text{J}} = 1.3491 \, \text{MeV}
\]

\[1.3491 \, \text{MeV} \] is produced by the reaction.

**Q21.4.25**

A \( \ce{^8_5B} \) atom (mass = 8.0246 amu) decays into a \( \ce{^8_4Be} \) atom (mass = 8.0053 amu) by loss of a \( \beta^+ \) particle (mass = 0.00055 amu) or by electron capture. How much energy (in millions of electron volts) is produced by this reaction?

**S21.4.25**

Using Einstein's equation, \( E=mc^2 \)

we can alter it so that we can account for the change in mass indicated in the problem so that it looks like this:

\[ \Delta E = \Delta mc^2 \]

such that \( \Delta E = \) change in energy, \( \Delta m = \) change in mass, \( c = \) speed of light (\( \sim 3.0 \times 10^8 \))

Since the problem states that this problem involves a loss of a \( \beta^+ \) particle or by electron capture, we write the equation as follows:

\[ \ce{^5_8}B \to \ce{^4_8}B + \ce{^0_1}\beta^+ \]

Now we have to calculate for the \( \Delta m \): \( \Delta m = m_{\text{reactants}} - m_{\text{products}} \)

To find the mass of the products we multiply by the masses of protons/neutrons by the number of each on the product side.

\( (8.0246 \text{amu}) - (8.0053 \text{amu} + 0.00055) \)

\( \Delta m = 0.01875 \text{ amu} \)

Since in the equation, \( \Delta m \) is in kilograms. We convert the 0.01985 amu to kg.

In order to do so, we have to divide 0.01985 amu by Avogadro’s number (\( (6.022 \times 10^{23}) \)) to convert into grams. Then divide by 1000 g to convert to kg.

\( \frac{0.01875}{6.022 \times 10^{23}} \times \frac{1 \text{ kg}}{1000 \text{ g}} = 3.1136 \times 10^{-29} \text{ kg} \)

Now we can plug in \( \Delta m \) and the speed of light, \( c \) into the equation yielding: \( \Delta E = (3.1136 \times 10^{-29} \text{ kg})(3.00 \text{ /time} 10^8 \text{ m/s})^2 \)
To convert to volts, we multiply \((-2.8022 \times 10^{-12})\) back by Avogadro's number to the units to be J/mol

$$= 1.6875 \times 10^{12} \text{ J/mol}$$

To convert to volts, we need to divide by Faraday's constant: $$\frac{1.6875 \times 10^{12} \text{ J/mol}}{96485 \text{ J/mol V}}$$

which yields us the final answer $$= 17.5 \text{ MeV}$$

**Q21.4.26**

Isotopes such as $^{26}\text{Al}$ (half-life: $7.2 \times 10^5$ years) are believed to have been present in our solar system as it formed, but have since decayed and are now called extinct nuclides.

a. $^{26}\text{Al}$ decays by $\beta^+$ emission or electron capture. Write the equations for these two nuclear transformations.

b. The earth was formed about $4.7 \times 10^9$ (4.7 billion) years ago. How old was the earth when 99.999999% of the $^{26}\text{Al}$ originally present had decayed?

**S21.4.26**

1. $\beta^+$ emission is the decay of an isotope by a fast moving beta particle or an electron, which is represented by $^{0}_{-1}e$. The mass number is 0, and the atomic number is -1. Since this is an emission or a decay, we put the electron on the products, and reduce the atomic number of particle by 1. This results in an atomic number of 14, which is the atomic number of silicon. If we put all this information together, we get an equation like so:

$$^{26}_{13}\text{Al} \xrightarrow{^{0}_{-1}e}^{0}_{-1}e + ^{26}_{14}\text{Si}$$

In an electron capture, the electron $^{0}_{-1}e$ is used, but it is used in the reactant side of the equation because it is capture. In addition, a neutrino is involved which is represented by $^{0}_{0}v$ because it is ejected from the nucleus where the electron reacts with the isotope, so it is represented in the product side of the equation. Putting it all together, you get an equation like so:

$$^{26}_{13}\text{Al} + ^{0}_{-1}e \xrightarrow{^{0}_{0}v} ^{0}_{0}v + ^{26}_{12}\text{Mg}$$

2. Half life is represented by this equation, where $\lambda=\text{constant}$:

$$\lambda = \frac{0.693}{t_{1/2}}$$

Plugging in numbers: $\lambda = \frac{0.693}{(7.2 \times 10^5)} = (9.63 \times 10^{-7})$ years

If 99.999999% decayed, then about 0.000001% remains
To solve this problem, we use this equation:

\[ \ln \left( \frac{n_t}{n_0} \right) = -\lambda t \]

\( \lambda \) = decay constant, given by the constant we calculated above \((9.63 \times 10^{-7})\) years

\( n_t \) = concentration of isotope at time t (0.000001)

\( n_0 \) = initial concentration of isotope (100)

We plug all the numbers in and calculate for t

\[ \ln \left( \frac{0.000001}{100} \right) = -(9.63 \times 10^{-7})t \]

\( t = 19128432.76 \) years

We can round this to about 19,128,433 years

To find out how old the earth was when 99.999999\% decayed we subtract this number from the age of earth:

4,700,000,000 years - 19,128,433 years = 4,680,871,567 years

\[ \text{A21.4.26} \]

a)

\[ ^{26}_{13}\text{Al} \rightarrow ^{0}_{-1}\text{e} + ^{26}_{14}\text{Si} \]

\[ ^{26}_{13}\text{Al} + ^{0}_{-1}\text{e} \rightarrow ^{0}_{0}\nu + ^{26}_{12}\text{Mg} \]

b)

4,680,871,567 years

\[ \text{Q21.4.27} \]

Write a balanced equation for each of the following nuclear reactions:

a. bismuth-212 decays into polonium-212
b. beryllium-8 and a positron are produced by the decay of an unstable nucleus

\[ \text{c. neptunium-239 forms from the reaction of uranium-238 with a neutron and then spontaneously converts into plutonium-239} \]

d. strontium-90 decays into yttrium-90

\[ \text{S21.4.27} \]

a. bismuth-212 decays into polonium-212
Step 1: Determine the atomic and mass number of the elements.

Bismuth-212 has an atomic number of 83 so we write it as, \(_{83}^{212}\text{Bi}\), Polonium-212 has an atomic number of 84, \(_{84}^{212}\text{Po}\)

Step 2: Determine the type of radiation that is emitted by the reaction.

The atomic number increased by one so we can determine that it is emitting a beta particle, \(_{-1}^{0}\text{e}\)

Step 3: Write equation

\[{}_{83}^{212}\text{Bi} \rightarrow {}_{84}^{212}\text{Po} + {}_{-1}^{0}\text{e}\]

Step 4: Make sure that both sides are balance, equal to each other

Mass number 212 → 212 + 0

Atomic number 83 → 84 + -1

a. Solution

\[{}_{83}^{212}\text{Bi} \rightarrow {}_{84}^{212}\text{Po} + {}_{-1}^{0}\text{e}\]

b. beryllium-8 and a positron are produced by the decay of an unstable nucleus

Step 1: Determine atomic number

Beryllium: \(_{4}^{8}\text{Be} \) Positron: \(_{+1}^{0}\text{e}\)

Step 2: Find unknown nucleus

Since its a beta decay (positron), you know that the atomic number increases by 1 and there is no change in the molar mass, therefore atomic number= 1+ 4= 5, which is boron.

Unknown element is \(_{5}^{8}\text{B} \)

Step 3: Write equation

\[{}_{5}^{8}\text{B} \rightarrow {}_{4}^{8}\text{Be} + {}_{+1}^{0}\text{e}\]

Step 4: Check

Mass number 8 → 8 + 0

Atomic number 5 → 4 + 1

b. Solution
c. neptunium-239 forms from the reaction of uranium-238 with a neutron and then spontaneously converts into plutonium-239

Step 1: Write equation given

You are told that neptunium-239 forms from uranium-238 an a neutron, \(_{0}^{1}\text{n}\). You also know that its a beta emission, electron, because the atomic number goes from 92 in uranium to 93 in neptunium.

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

Step 2: Account for the spontaneous part

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

c. Solution

$$(_{92}^{238}\text{U}+_{0}^{1}\text{n})\rightarrow (_{93}^{239}\text{Np}+_{-1}^{0}\text{e}),\quad (_{93}^{239}\text{Np})\rightarrow (_{94}^{239}\text{Pu}+_{-1}^{0}\text{e})$$

d. Strontium-90 decays into yttrium-90

Step 1: Find atomic number

Strontium-90 has an atomic number of 38: \(_{38}^{90}\text{Sr}\) Yttrium-90 has an atomic number of 39: \(_{39}^{90}\text{Y}\)

Step 2: Determine the type of radioactivity

Since the mass number is constant and the atomic number changes by one its a beta emission, specifically a \(_{-1}^{0}\text{e}\)

Step 3: Write equation

$$(_{38}^{90}\text{Sr})\rightarrow (_{39}^{90}\text{Y}+_{-1}^{0}\text{e})$$

Step 4: Check

Mass number 90 \(\rightarrow\) 90 + 0

Atomic number 38 \(\rightarrow\) 39 + -1

d. Solution
Write a balanced equation for each of the following nuclear reactions:

a. mercury-180 decays into platinum-176
   
   Solution: Mercury has 80 protons. Platinum has 78. The change in the number of particles is 2 protons. The mass changes from 180 to 176 which is a change of 4 units. This decay ratio is typical of alpha decay which is a He\(^{2+}\) particle.

   \[ ^{180}_{80}\text{Hg} \rightarrow ^{4}_{2}\alpha + ^{176}_{78}\text{Pt} \]

b. zirconium-90 and an electron are produced by the decay of an unstable nucleus

   Solution: An electron has the symbol \(^0_{-1}\text{e}^-\). The mass number and atomic number of the products (an electron and zirconium-90) of the decay of an unstable nucleus must add up to the mass number and atomic number of the unstable species. \(^{90}_{39}\text{Y} + ^0_{-1}\text{e}^- \rightarrow ?\). The sum of the mass numbers 90-0=90 means that the unknown has a mass number of 90 as well. The sum of the atomic numbers 40+-1=39 reveals the number of protons the unstable element had. Yttrium has 39 protons meaning that the nuclear reaction is:

   \[ ^{90}_{39}\text{Y} \rightarrow ^{90}_{40}\text{Zr} + ^0_{-1}\text{e}^- \]
3. thorium-232 decays and produces an alpha particle and a radium-228 nucleus, which decays into actinium-228 by beta decay

**Solution:** Thorium 232 has 90 protons and 142 neutrons. If its radioactive decay produces an alpha particle it will also produce a particle with 2 fewer protons and 2 fewer neutrons. If the atomic number is 88 then the element produced is radium-228. If radium-228 produces a beta particle when decaying to actinium-228, that means that it produces an electron \(^{0}_{-1}e\)) and one neutron becomes a proton. The mass number will not change but the atomic number will.

\[
^{232}_{90}\text{Th} \rightarrow ^{228}_{88}\text{Ra} + ^4_2\alpha
\]

\[
^{228}_{88}\text{Ra} \rightarrow ^{228}_{89}\text{Ac} + ^0_{-1}\beta
\]

4. neon-19 decays into fluorine-19

**Solution:** Neon has an atomic number of 10 and Fluorine has an atomic number of 9. Their mass numbers are the same but their atomic numbers are different indicating that the emitted particle has a mass number of 0 and an atomic number of 1 (positron). Therefore the decay is that of beta\(^+\) On each side of the arrow the atomic numbers and the mass numbers should be equal.

\[
^{19}_{10}\text{Ne} \rightarrow ^{19}_{9}\text{F} + ^0_{-1}\beta
\]

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**A21.4.28**

a)\(^{180}_{80}\text{Hg} \rightarrow ^4_2\alpha + ^{176}_{78}\text{Pt}\)

b)\(^{90}_{39}\text{Y} \rightarrow ^{90}_{40}\text{Zr} + ^0_{-1}e\)

c)\(^{232}_{90}\text{Th} \rightarrow ^{228}_{88}\text{Ra} + ^4_2\alpha\)

\[
^{228}_{88}\text{Ra} \rightarrow ^{228}_{89}\text{Ac} + ^0_{-1}\beta
\]

d)\(^{19}_{10}\text{Ne} \rightarrow ^{19}_{9}\text{F} + ^0_{-1}\beta\)

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**21.5: Transmutation and Nuclear Energy**

**Q21.5.1**

Write the balanced nuclear equation for the production of the following transuranium elements:

a. berkelium-244, made by the reaction of Am-241 and He-4
b. fermium-254, made by the reaction of Pu-239 with a large number of neutrons
c. lawrencium-257, made by the reaction of Cf-250 and B-11
d. dubnium-260, made by the reaction of Cf-249 and N-15
S21.5.1

a. From the given information we can write the nuclear equation
\[ ^{241}_{95}\text{Am} +^4_2\text{He}\rightarrow ^{244}_{97}\text{Bk} \]

On the left side the total mass number is
\[ 241 + 4 = 245 \]

and the total atomic number is
\[ 95 + 2 = 97 \]

On the right side the total mass number is 244 and the total atomic number is 97. This shows that one neutron needs to be added which would increase the total mass number needs to by one while keeping the total atomic number the same. The balanced nuclear equation would be
\[ ^{241}_{95}\text{Am} +^4_2\text{He}\rightarrow ^{244}_{97}\text{Bk}+^1_0\text{n} \]

b. From the given information we can write the nuclear equation
\[ ^{239}_{94}\text{Pu}+\text{x }^1_0\text{n}\rightarrow^{254}_{100}\text{Fm} \]

On the left side we see that the total mass number is the sum of \( 239+(1)\text{x}\). on the right side we see that the total mass number is 254. since the total mass number of the reactants must equal that of the products we can write
\[ 239+\text{x}=254 \]

showing 15 neutrons need to be added to balance the mass number.
\[ ^{239}_{94}\text{Pu}+15\text{ }^1_0\text{n}\rightarrow^{254}_{100}\text{Fm} \]

To balance the total atomic number of the equation, 6 electrons need to be added to the right side. Therefore the balanced equation reads:
\[ ^{239}_{94}\text{Pu}+15\text{ }^1_0\text{n}\rightarrow^{254}_{100}\text{Fm}+\text{6 }^0_{-1}\text{e} \]

c. From the given information we can write the nuclear equation
\[ ^{250}_{98}\text{Cf}+\text{^{11}_5B}\rightarrow^{257}_{103}\text{Lr} \]

On the left side the total mass number is
\[ 250+11=261 \]

and the total atomic number is
\[ 98+5=103 \]
On the right side the total mass number is 257 and the total atomic number is 103. This means that 4 neutrons need to be added to the right side to balance the equation. The balanced nuclear equation is

\[ ^{250}_{98}\text{Cf}+^{11}_5\text{B}\rightarrow^{257}_{103}\text{Lr}+4^1_0\text{n} \]

d. From the given information we can write the nuclear equation

\[ ^{249}_{98}\text{Cf}+^{15}_7\text{N}\rightarrow^{260}_{105}\text{Db} \]

On the left side the total mass number is 249+15=264 and the total atomic number is 98+7=105.

On the right side the total mass number is 260 and the total atomic number is 105. This means that 4 neutrons need to be added to the right side to balance the equation. The balanced nuclear equation is

\[ ^{249}_{98}\text{Cf}+^{15}_7\text{N}\rightarrow^{260}_{105}\text{Lr}+4^1_0\text{n} \]

**Q21.5.1**

a. \( ^{241}_{95}\text{Am} + ^4_2\text{He} \rightarrow ^{244}_{97}\text{Bk} + ^1_0\text{n} \);

b. \( ^{239}_{94}\text{Pu} + 15^1_0\text{n} \rightarrow ^{254}_{100}\text{Fm} + 6^0_{-1}\text{e} \);

c. \( ^{250}_{98}\text{Cf} + ^{11}_5\text{B} \rightarrow ^{257}_{103}\text{Lr} + 4^0\text{n} \);

d. \( ^{249}_{98}\text{Cf} + ^{15}_7\text{N} \rightarrow ^{260}_{105}\text{Db} + 4^1_0\text{n} \)

**Q21.5.2**

How does nuclear fission differ from nuclear fusion? Why are both of these processes exothermic?

**S21.5.2**

Nuclear fusion is the process in which small atoms are put together to make larger ones. Nuclear fission is the process in which a heavy element nucleus splits into two or more medium-sized nuclei as the result of the bombardment. During both processes, some mass is converted into energy following \( E=mc^2 \), \( m \) comes from the mass defect.

**Q21.5.3**

Both fusion and fission are nuclear reactions. Why is a very high temperature required for fusion, but not for fission?
S21.5.3
Two nuclei must collide for fusion to occur. High temperatures are required to give the nuclei enough kinetic energy to overcome the very strong repulsion resulting from their positive charges. Fission does not have to overcome nuclear repulsion and therefore has a low activation energy.

Q21.5.4
Cite the conditions necessary for a nuclear chain reaction to take place. Explain how it can be controlled to produce energy, but not produce an explosion.

S21.5.4
Chain reactions involve fission reactions which produce more chain reactions through the products that are created. A fission reaction is an event where a larger nucleus breaks apart into smaller nuclei, and the produced nuclei are often more stable with some exceptions. One of the conditions of a nuclear chain reaction is fission for a large quantity of an element. The best example of a way that nuclear chain reactions can be controlled to produce energy but not an explosion are nuclear plants. This is because controlled chain reactions occur in nuclear reactors with many different components. These components are:

1) **Fuel Element**: Usually uranium or plutonium which undergo fission to provide nuclear energy.

2) **Moderator**: Causes neutrons to slow down in order to achieve thermal energy range.

3) **Coolant**: Reduces the heat produced by the fission reaction by absorbing it.

4) **Control Rods**: Reduces the number of neutrons available to continue the chain reaction by absorbing them. Without a limit to neutron production energy released rises very quickly

If all of these factors are running smoothly and there are no errors in the system, the nuclear chain reaction can be controlled to produce energy. If an error does occur, this causes accidental destructive chain reactions which results in an explosion when too much energy is produced.

Q21.5.5
Describe the components of a nuclear reactor.

S21.5.5
A nuclear reactor is a machine in which heat is produced due to nuclear fission (splitting of atoms) chain reaction for the generation of electricity. The energy released from continuous fission of the atoms of the fuel is used as heat in a gas or water form, producing steam in the process. The steam then moves the turbines to make electricity (as in most fossil fuel plants).

A nuclear reactor consists of the following:
• **Nuclear fuel.** A unstable isotope must be present in a large amount to sustain a controlled chain reaction. The radioactive isotope is contained in tubes called fuel rods.

• **Moderator.** A moderator slows neutrons from high velocities and high energy produced by nuclear reactions. Since energy is conserved, this reduction of the neutron kinetic energy takes place by transfer of energy to the moderator. A moderator also causes the probability of a neutron hitting the fuel rods to increase.

• **Coolant.** It's a fluid circulating through the core to transfer the heat from the fission reaction to an external boiler and turbine where it is transformed into electricity. Coolants also serve to maintain manageable pressures within the core. In most nuclear reactors, the coolant is ordinary water that is under high pressure.

• **Control system.** The control system consists of control rods, which are used to control the rate of fission in a nuclear reactor. It is placed between fuel rods to absorb neutrons and is used to adjust the number of neutrons and keep the rate of the chain reaction at a safe level. It also has sensors which supply measured data, programmable controllers to process those signals, and monitors.

• **A shield and containment system.** The function of this component is to protect workers from radiation produced by the nuclear reactions and to withstand the high pressures resulting from high-temperature reactions. It also is used to protect from any serious malfunctions within the reactor. It is typically a meter-thick concrete and steel structure. They are the last barrier between the reactor and the outside environment.

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**Q21.5.6**

In usual practice, both a moderator and control rods are necessary to operate a nuclear chain reaction safely for the purpose of energy production. Cite the function of each and explain why both are necessary.

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**S21.5.6**

**Moderator:**

The neutron moderator is a material or substance in the core of the reactor responsible for slowing down high velocity neutrons produced by fission. This increases the likelihood of the neutrons interacting with the nuclear fuel (e.g. Uranium-235 or Plutonium-239), sustaining the nuclear chain reaction and continuously releasing the heat used to generate electricity. Water is usually the medium of choice for the moderator, but deuterium-based heavy water or graphite are sometimes used in other countries.

**Control Rods:**

Control rods are used to maintain control of the reaction. Usually made of a neutron-absorbing material such as silver, indium or cadmium, the control rod is able to absorb neutrons produced during the fission reaction providing greater control over the rate of reaction. Control rods are usually left partially inserted into the central core in order to sustain a manageable chain reaction, but can be further inserted to decrease the rate of the chain reaction or be completely removed from the core to delimit the reaction (melt down).

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**Q21.5.7**

Describe how the potential energy of uranium is converted into electrical energy in a nuclear power plant.
S21.5.7

Nuclear Reactors produce electricity, and unlike conventional plants that burn coal and fuel and produce electricity through boiling water into steam, nuclear reactors use uranium fuel through the process of fission to create steam. The uranium at the beginning is stored in ceramic pellets that are placed inside the nuclear reactor. Through fission, the uranium atoms are split into smaller elements, and additionally releases neutrons. Those neutrons are slowed down by a moderator and the momentum lost is turned into heat. The heat that is created through the splitting of the uranium atoms creates the steam necessary to drive the turbine. The driving of the turbine spins the generator, and that in turn creates the electricity. **Through the process of fission within the nuclear power plant, the potential energy in uranium turns into heat, which then creates electricity.**

Q21.5.7

The mass of a hydrogen atom \(\text{(}^1_1\text{H)}\) is 1.007825 amu; that of a tritium atom \(\text{(}^3_1\text{H)}\) is 3.01605 amu; and that of an α particle is 4.00150 amu. How much energy in kilojoules per mole of \(\text{(}^4_2\text{He)}\) produced is released by the following fusion reaction: \(\text{(}^1_1\text{H} + ^3_1\text{H} \rightarrow ^4_2\text{He}\)).

S21.5.8

Since we were asked for the energy in kilojoules released by the reaction we need to use the equation: \(\Delta E=\Delta mc^2\)

We need to find \(\Delta m\)

Step1: Total mass before the reaction \(\text{(}^1_1\text{H}+^3_1\text{H}\))

\[1.007825 + 3.01605 = 4.023875 \text{ amu}\]

Step2: total mass after the reaction \(\text{(}^4_2\text{He}\))

\[4.00150 \text{ amu (α particle)}\]

Step 3: Mass defect \(\Delta m\)

\[\Delta m = \text{mass(reactants)} - \text{mass(products)}\]

\[\Delta m = 4.023875 \text{amu} - 4.00150 \text{amu} = 0.022375 \text{ amu}\]

Since \[1 \text{amu} = 1.6605 \times 10^{-27} \text{kg}\]

The mass defect equals to: \[0.022375 \text{amu} \times 1.6605 \times 10^{-27} \text{kg/amu} = 3.715 \times 10^{-29} \text{ kg}\]

Energy released: \[\Delta E = \Delta mc^2\]

Therefore, \[\Delta E = 3.715 \times 10^{-29} \times (3 \times 10^8)^2 = 3.3438 \times 10^{-12} \text{J}\]
since \[1000 J = 1 \text{ kJ}\]

Binding Energy \[\Delta E = 3.3438 \times 10^{-15} \frac{\text{kJ}}{\text{atom}}\]

Since there are \[\text{Na} = 6.022 \times 10^{23} \frac{\text{atoms}}{\text{mol He}}\]

The binding energy for one mole of \(\text{He}\) will be \[\Delta E = 3.3438 \times 10^{-15} \frac{\text{kJ}}{\text{atom}} \times 6.022 \times 10^{23} \frac{\text{atom}}{\text{mole}} = 2.0129 \times 10^{9} \frac{\text{kJ}}{\text{mole}}\]

### 21.6: Uses of Radioisotopes

**Q21.6.1**

How can a radioactive nuclide be used to show that the equilibrium:

\[\text{AgCl}(s) \rightleftharpoons \text{Ag}^+(aq) + \text{Cl}^-(aq)\]

is a dynamic equilibrium?

**S21.6.1**

Radiotracers, or radioisotopes (radioactive isotopes) of either \(\text{Ag}^+\) or \(\text{Cl}^-\) can be introduced into the solution. This will cause the reaction to shift left (according to Le Chatelier's principle), producing more of the \(\text{AgCl}(s)\). After giving time for the system to equilibrate, if radioactive precipitates are present, a dynamic equilibrium has been established.

**Q21.6.2**

Technetium-99m has a half-life of 6.01 hours. If a patient injected with technetium-99m is safe to leave the hospital once 75% of the dose has decayed, when is the patient allowed to leave?

**S21.6.2**

Each element has a specific half-life where the original concentration decayed into half. In this case, the half-life Technetium-99m is 6.01 hr. In nuclear kinetic, all radioactive decay is first-order process \((\ln(N/N_0)=-kt)\), thus its radioactive half-lives follow the first order half-life's formula \(t_{1/2} = \frac{\ln(2)}{k}\).

Step 1: Determine the decay rate constant \(k\) using the formula the following formula: \([t_{1/2} = \ln(2)/k]\)

\[6.01 = \ln(2)/k\]

\[k = \ln(2)/6.01\]

\[k = 0.1153 \text{ hr}^{-1}\]
Step 2: Determine the time that takes for 75% of Technetium-99m to decay using the formula, \( \ln(N/N_0) = -kt \):

Note: 75% can be written as 0.75, which means that \( N(\text{final concentration}) = 1 - 0.75 = 0.25 \) since 75% has decayed and \( N_0(\text{original concentration}) = 1 \) since it is assume that the patient was injected 100% in the beginning.

\[
\ln(0.25/1) = -0.1153(t) \]

\[
t = \frac{\ln(0.25/1)}{-0.1153} \]

\[
t = 12.02 \text{ hrs} \]

This means that patient injected with technetium-99m is safe to leave the hospital after 12.02 hrs since 75% of the dose has decayed.

A21.6.2

12.02 hours

Q21.6.3

Iodine that enters the body is stored in the thyroid gland from which it is released to control growth and metabolism. The thyroid can be imaged if iodine-131 is injected into the body. In larger doses, I-131 is also used as a means of treating cancer of the thyroid. I-131 has a half-life of 8.70 days and decays by \( \beta^- \) emission.

a. Write a nuclear equation for the decay.

b. How long will it take for 95.0% of a dose of I-131 to decay?

S21.6.3

a. In the problem, we are given that the type of decay is \( \beta^- \) emission which can be represented by: \( \ce{^0_{-1}e} \)

By looking at the periodic table, we see that Iodine has an atomic number of 53.

We can start out by writing:

\[
\ce{^{133}_{53}I} \rightarrow \ce{?} + \ce{^0_{-1}e} \]

To complete the equation, we need to find out what " \( \ce{?} \) " is. All equations need to balance to conform to the two conservation laws: the mass number and the electrical charge.

Using the conservation laws to find the unknown, \( ? \), in a nuclear reaction equation, we get \( \ce{(?)} = \ce{(^{A}_{Z}\text{ElementalSymbol})} \) in which \( A \) is the sum of the total number of protons, \( Z \), and neutrons. We find that \( A = 133 - 0 = 133; Z = 53 - (-1) = 54. \) Looking up the periodic table, we find that Xenon(Xe) has an atomic number of 54. Putting everything together, we get the equation for the decay to be:
\[ ^{133}_{53}I \rightarrow ^{133}_{54}Xe + ^{0}_{-1}e \]

**b.**

We are given that the half-life \( t_{1/2} \) is 8.70 days.

First thing we have to do is find " \( k \) " We can do this by using the following equation:

\[ t_{1/2} = \frac{0.693}{k} \]

Solving for " \( k \) " and plugging in \( t_{1/2} = 8.70 \) days, we get " \( k \) " to be:

\[ k = \frac{0.693}{8.70} = 0.07966 \]

Radioactive decay is a first-order process and can be described in the terms of the integrated rate law:

\[ \ln\left(\frac{N}{N_0}\right) = -kt \]

where \( N_0 \) is the initial amount available and \( N \) is the amount at some time, \( t \).

If 95.0% has decayed, that means that there is 100%-95.0%= 5.0% of the dose left. For instance, let's say we start out with 100 grams, that is, \( A_0 = 100 \). If 95.0% of this amount has decayed, that means there's only 5 grams left ( \( A = (0.95)(100) = 5 \) ).

Plugging these values into the integrated rate law above, we can find out the time, \( t \), it will take 95.0% of the dose to decay:

\[ \ln\left(\frac{5}{100}\right) = -0.07966t \]

\[ t = 37.6 \text{ days} \]

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21.7: Biological Effects of Radiation

Q21.7.1

If a hospital were storing radioisotopes, what is the minimum containment needed to protect against:
a. cobalt-60 (a strong γ emitter used for irradiation)
b. molybdenum-99 (a beta emitter used to produce technetium-99 for imaging)

S21.7.1

An unstable nucleus may emit particles such as alpha particles, beta particles, and gamma particles to attain a stable configuration.

An alpha particle (α) is a helium atom that relatively easy to stop and is the least penetrating radioactive decay.

\(_2^4\text{He}\)

A beta particle (β) is an electron that has high energy that is released during the radioactive decay of the unstable nucleus.

\(_{-1}^0\text{e}\)

A gamma ray (γ) is part of the electromagnetic particles that have high energy and are emitted by nuclei in an excited state attempting to return to their ground state.

\(_0^0\gamma\)

Figure 24.2: The Ability of Different Types of Radiation to Pass Through Material, from Least to Most Penetrating.

1. cobalt-60 (a strong γ emitter used for irradiation)

Cobalt-60 is a source of gamma transmitters. Gamma rays are more penetrating than either alpha and beta radiation, it can penetrate the skin and damage cells, go through water and concrete and can only be stopped by a thick layer of lead.

2. molybdenum-99 (a beta emitter used to produce technetium-99 for imaging)
Molybdenum-99 is a source of beta emitters. Beta particles have moderate ionizing radiation but are however far more powerful than an alpha emission. Although it's more powerful than alpha emission, it's still far less energized in comparison to a gamma emission and will be stopped by a thin sheet of metal.

A21.7.1

a) Thick layer of lead
b) Thin sheet of metal

Q21.7.2

Based on what is known about Radon-222’s primary decay method, why is inhalation so dangerous?

S21.7.2

Alpha particles can be stopped by very thin shielding but have much stronger ionizing potential than beta particles, X-rays, and γ-rays. When inhaled, there is no protective skin covering the cells of the lungs, making it possible to damage the DNA in those cells and cause cancer as helium nuclei are small.

Q21.7.3

Given specimens uranium-232 ($t_{1/2} = \mathrm{68.9 \; y}$) and uranium-233 ($t_{1/2} = \mathrm{159,200 \; y}$) of equal mass, which one would have greater activity and why?

S21.7.3

Activity is the rate of decay of a radioactive sample of matter. The integrated activity equation is $A = kN$, where $N$ is the number of atoms of a radioactive isotope left in a sample, and $k$ is the decay rate constant. Because radioactivity is a first order process, we know that $t_{1/2} = \ln2/k$.

Looking at uranium-232, and the average half-life of 68.9, and solving for $k$, we find:

\[ k = \frac{\ln2}{68.9} = 0.0100 \]

Looking at uranium-233, and the average half-life of 159,200, and solving for $k$, we find:

\[ k = \frac{\ln2}{159,200} = 4.35 \times 10^{-6} \]

If we look back at the activity equation $A = kN$, and think about how each decay constant $k$ would affect the activity, we see that the larger $k$ would produce a larger activity. Therefore, because 0.0100 is the larger decay constant, uranium-232 has a greater activity.
A21.7.3
Uranium-232

Q21.7.4
A scientist is studying a 2.234 g sample of thorium-229 ($t_{1/2} = 7340$ y) in a laboratory.

a. What is its activity in Bq?

b. What is its activity in Ci?

S21.7.4
(a) $7.64 \times 10^9$ Bq; (b) $2.06 \times 10^{-2}$ Ci

Q21.7.5
Given specimens neon-24 ($t_{1/2} = 3.38$ min) and bismuth-211 ($t_{1/2} = 2.14$ min) of equal mass, which one would have greater activity and why?