Phenomena: Below is a list of stable isotopes of different elements. Examine the data and see what patterns you can identify. The mass of an electron is 0.00055 u, the mass of a proton is 1.00728 u, and the mass of a neutron is 1.00867 u.

<table>
<thead>
<tr>
<th>Element</th>
<th>Number of e⁻</th>
<th>Number of p⁺</th>
<th>Number of n</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1.00794 u</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2.01355 u</td>
</tr>
<tr>
<td>Si</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>27.97693 u</td>
</tr>
<tr>
<td>Si</td>
<td>14</td>
<td>14</td>
<td>15</td>
<td>28.97649 u</td>
</tr>
<tr>
<td>Fe</td>
<td>26</td>
<td>26</td>
<td>30</td>
<td>55.93539 u</td>
</tr>
<tr>
<td>Fe</td>
<td>26</td>
<td>26</td>
<td>32</td>
<td>57.93328 u</td>
</tr>
<tr>
<td>Ag</td>
<td>47</td>
<td>47</td>
<td>60</td>
<td>106.90510 u</td>
</tr>
<tr>
<td>Ag</td>
<td>47</td>
<td>47</td>
<td>62</td>
<td>108.90475 u</td>
</tr>
<tr>
<td>Pt</td>
<td>78</td>
<td>78</td>
<td>116</td>
<td>193.96268 u</td>
</tr>
<tr>
<td>Pt</td>
<td>78</td>
<td>78</td>
<td>118</td>
<td>195.96495 u</td>
</tr>
</tbody>
</table>
**Big Idea:** Changes in the nucleus of an atom can result in the ejection of particles, the transformation of the atom into another element, and the release of energy.
Nucleus (plural nuclei): Mass at the center of an atom where protons and neutrons are located.

Nucleon: A particle in an atomic nucleus, either a proton or a neutron.

Nuclear Decay: The process by which a nucleus of an unstable atom loses energy by emitting particles and/or energy.

Kinetic Stability: The probability that a nucleus will undergo decomposition to form a different nucleus.

Note: If a problem asks for energy per nucleon, divide the energy by the mass number (A).
Henri Becquerel stored uranium oxide in a drawer with photographic plates. The uranium oxide darkened the plates therefore the uranium oxide must have given off some type of radiation.
Nuclear Decay

- Ernest Rutherford passed the radiation through two electrically charged plates and found that the radiation was made up of three primary particles (α, β, and γ) each having a different charge.
## Nuclear Decay

<table>
<thead>
<tr>
<th>Name of Radiation</th>
<th>What is Emitted</th>
<th>How it Appears in Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha (α)</td>
<td>Helium nucleus (2 protons and 2 neutrons)</td>
<td>$^4_2He$</td>
</tr>
<tr>
<td>Beta (β)</td>
<td>electron</td>
<td>$^-1_0e$ or $β^-$</td>
</tr>
<tr>
<td>Gamma (γ)</td>
<td>Electromagnetic radiation</td>
<td>Does not appear in equation</td>
</tr>
</tbody>
</table>

**Note:** Shorthand notation $^A_Z$element symbol where $A$ is the mass number ($A=n+p$) and $Z$ is the atomic number ($Z=p$).
**Nuclear Decay**

**TABLE 20.2**
Various Types of Radioactive Processes Showing the Changes That Take Place in the Nuclides

<table>
<thead>
<tr>
<th>Process</th>
<th>Change in (A)</th>
<th>Change in (Z)</th>
<th>Change in Neutron/Proton Ratio</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\beta)-Particle (electron) production</td>
<td>0</td>
<td>+1</td>
<td>Decrease</td>
<td>(^{227}_{89}\text{Ac} \rightarrow ^{227}_{90}\text{Th} + ^{0}_{1}\text{e})</td>
</tr>
<tr>
<td>Positron production</td>
<td>0</td>
<td>−1</td>
<td>Increase</td>
<td>(^{13}_{7}\text{N} \rightarrow ^{13}_{6}\text{C} + ^{0}_{1}\text{e})</td>
</tr>
<tr>
<td>Electron capture</td>
<td>0</td>
<td>−1</td>
<td>Increase</td>
<td>(^{73}_{33}\text{As} + ^{0}_{1}\text{e} \rightarrow ^{73}_{32}\text{Ge})</td>
</tr>
<tr>
<td>(\alpha)-Particle production</td>
<td>−4</td>
<td>−2</td>
<td>Increase</td>
<td>(^{210}_{84}\text{Po} \rightarrow ^{206}_{82}\text{Pb} + ^{4}_{2}\text{He})</td>
</tr>
<tr>
<td>(\gamma)-Ray production</td>
<td>0</td>
<td>0</td>
<td>—</td>
<td>Excited nucleus \rightarrow\text{ground-state nucleus} + ^{0}_{0}\gamma</td>
</tr>
<tr>
<td>Spontaneous fission</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>(^{254}_{98}\text{Cf} \rightarrow\text{lighter nuclides} + \text{neutrons})</td>
</tr>
</tbody>
</table>

- Scientists have discovered other types of particles but these types of radiation are far less common than \(\alpha\), \(\beta\), and \(\gamma\) radiation.
- **Positron Production**: A mode of nuclear decay in which a particle is formed having the same mass as an electron but opposite in charge. (positron= \(^0\_1\text{e}\))
- **Electron Capture**: A process in which one of the inner-orbital electrons in an atom is captured by the nucleus.
Student Question

Identify the nucleus produced by electron capture of beryllium-7 (Z = 4)

a) $^7_3Li$  
b) $^7_5B$  
c) $^3_2He$  
d) None of the Above

Identify the nucleus produced by positron emission of sodium-22 (Z = 11)

a) $^{22}_{10}Ne$  
b) $^{22}_{12}Mg$  
c) $^{18}_{9}F$  
d) None of the Above
The number of elements with even atomic numbers are more abundant than the elements with odd atomic numbers.

Nuclei are more likely to be stable if they are built from certain numbers of either kind of nucleons. These numbers “magic numbers” include 2, 4, 8, 20, 50, 82, 114, 126, and 184.
A band of stability is found with a sea of instability at either side. For low atomic numbers, the band of stability lies on the $A = 2Z$ line. As the atomic number increases the protons repel each other more, making it necessary for more neutrons to be present in the nucleus.
Student Question

Which of the following processes does not help $^{145}_{64}Gd$ (proton rich) become more stable?

a) Electron Capture  
b) Beta Particle Emission  
c) Positron Emission  
d) Proton Emission
Radioactive series is a series of radioactive decays that a nucleus undergoes until a stable nucleus is formed.
Nuclear Radiation

- **Positive Impacts of Nuclear Radiation**
  - Can be used to kill unwanted tissue (cancer)
  - Radiotracers
  - Isotopic and carbon dating
  - Energy source
  - Preserving foods
  - Identification of reaction mechanisms
  - Powering spacecraft’s

- **Radiotracers**: A radioactive nuclide introduced into an organism for diagnostic purposes

- **Negative Impacts of Nuclear Radiation**
  - Radiation sickness
  - Nuclear bombs
  - Nuclear accidents
**Absorption Dose:** Is the energy deposited in a sample when it is exposed to radiation.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Absorbed Dose</td>
<td>rad</td>
<td>$10^{-2} \frac{J}{kg}$</td>
</tr>
<tr>
<td>Gray*</td>
<td>gy</td>
<td>$\frac{1}{kg}$</td>
</tr>
</tbody>
</table>

* SI unit

**Note:** 1 rad = $10^{-2}$ gy.
Radiation damage depends on type of radiation and the type of tissues.

**Relative biological effectiveness (Q):** A factor used when assessing the damage caused by a given dose of radiation.

Note: Q for β and γ radiation is arbitrarily set to about 1 which makes Q for α radiation about 20.

**Dose Equivalent:** Actual dose modified to take into account the different destructive powers. Dose equivalent = Relative biological effectiveness (Q) × adsorbed dose.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roentgen equivalent man</td>
<td>rem</td>
<td>$10^{-2}\frac{J}{kg}$</td>
</tr>
<tr>
<td>Sievert*</td>
<td>Sv</td>
<td>100 rem</td>
</tr>
</tbody>
</table>

* SI unit
Nuclear Radiation

- Average people get ~6 mSv (600 mrem) a year of background radiation.

<table>
<thead>
<tr>
<th>Percent</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>Radon seeping from the ground</td>
</tr>
<tr>
<td>30%</td>
<td>Cosmic rays</td>
</tr>
<tr>
<td>20%</td>
<td>Our own bodies</td>
</tr>
<tr>
<td>10%</td>
<td>Medical diagnosis</td>
</tr>
<tr>
<td></td>
<td>Typical chest x-ray ~0.07 mSv</td>
</tr>
</tbody>
</table>

- You can use this website to calculate your yearly radiation dose https://www.epa.gov/radiation/calculate-your-radiation-dose
**Activity:** The number of nuclear disintegrations per time.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curie</td>
<td>Ci</td>
<td>$3.7 \times 10^{10} \frac{\text{disintegrations}}{s}$</td>
</tr>
<tr>
<td>Becquerel*</td>
<td>Bq</td>
<td>$1 \frac{\text{disintegrations}}{s}$</td>
</tr>
</tbody>
</table>

* SI unit
Kinetics of Nuclear Decay

**Student Question**

The decay constant for fermium-254 is $210 \frac{1}{s}$. What mass of the isotope will be present if a sample of mass 1.00 $\mu$g is kept for 10 ms?

- a) $9.58 \times 10^{-913}$ $\mu$g
- b) 0.37 $\mu$g
- c) 0.75 $\mu$g
- d) None of the Above
Kinetics of Nuclear Decay

- Carbon Dating Reaction: $^{14}_6C \rightarrow ^{14}_7N + ^0_1e \quad t_{1/2}=5730 \text{ y}$

- Reaction that turns $N$ into $C$: $^{14}_7N + ^0_1n \rightarrow ^{14}_6C + ^1_1p$
A sample of carbon (250 mg) from wood found in a tomb in Israel underwent 2480 carbon-14 disintegration in 20. h. Estimate the time since death. A modern 1.0 g sample undergoes $1.84 \times 10^4$ disintegrations in the same time period. The half life of carbon-14 is 5730 years.

a) 357 years  
b) 5,105 years  
c) 16,563 years  
d) None of the Above
Nucleosynthesis: The formation of elements through nuclear processes.

Note: All elements that are beyond plutonium (94) are synthetic and produced by the bombardment of target nuclei.
Nuclear Energy

- **Nuclear Binding Energy** \( (E_{\text{bind}}) \): The energy released when protons and neutrons come together to form a nucleus.

- **Thermodynamic Stability**: The potential energy of a particular nucleus compared to the sum of the potential energies of its component protons and neutrons.
Ideal Calculation of Nuclear Binding Energy

- **Step 1:** Write the nuclear equation
  
  \[ x \cdot p + y \cdot n \rightarrow \text{nucleus} \]

- **Step 2:** Calculate the change in mass
  
  \[ \Delta m = \Sigma m(\text{prod}) - \Sigma m(\text{react}) = m_{\text{nucleus}} - (x \cdot m_p + y \cdot m_n) \]

- **Step 3:** Plug into \( E_{\text{bind}} = \Delta mc^2 \)

**Note:** It is hard to measure the mass of the nucleus without the mass of the electrons. It is much easier to use the molar mass which includes the mass of the electrons.

**Solution:** Use the mass of \( ^1_1H \) (1e\(^-\) and 1p) instead of the \( m_p \) this allows the mass of the e\(^-\) to cancel out.
How to Calculate the Nuclear Binding Energy

**Step 1:** Write the nuclear equation

\[ x \cdot ^1_1H + y \cdot n \rightarrow \text{atom} \]  
\( x = \# \text{ of } p = \# \text{ of } e^- \text{ and } y = \# \text{ of } n \)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutron</td>
<td>1.0087 u</td>
</tr>
<tr>
<td>(^1_1H)</td>
<td>1.0078 u</td>
</tr>
</tbody>
</table>

**Step 2:** Calculate the change in mass

\[ \Delta m = \Sigma m(\text{prod}) - \Sigma m(\text{react}) = m_{\text{atom}} - (x \cdot m_{^1_1H} + y \cdot m_n) \]

**Step 3:** Plug into \( E_{\text{bind}} = \Delta mc^2 \)

- \( E_{\text{bind}} \) means that energy was released or the nucleus is more stable than individual protons and neutrons.

**Note:** Binding energy are reported in eV  
1 eV = 1.602 \times 10^{-19} \text{ J}
Nuclear Energy

- A plot of the binding energy per nucleon vs. atomic number shows that the nucleons that are most strongly bonded together are near iron and nickel. This is one of the reasons that iron and nickel are abundant in meteorites and on rocky planets such as earth. Suggesting that nuclei of lighter atoms become more stable when they “fuse” together and that the heavier nuclei become more stable when they undergo “fission” and split into lighter nuclei.
Uranium-235 can undergo fission in the following reaction.

\[
\frac{235}{92}U + \frac{1}{0}n \rightarrow \frac{135}{52}Te + \frac{100}{40}Zr + \frac{1}{0}n
\]

Calculate the energy released when 1.0 g of uranium-235 undergoes fission in this way.

Helpful Information: \( m_{\frac{235}{92}U} = 235.04 \, u \),
\( m_{\frac{135}{52}Te} = 134.92 \, u \), \( m_{\frac{100}{40}Zr} = 99.92 \, u \), and \( m_n = 1.0087 \, u \)

a) \( 1.3 \times 10^{-13} \, J \)  
b) \( 3.0 \times 10^{-11} \, J \)  
c) \( 7.7 \times 10^{10} \, J \)  
d) None of the Above
Spontaneous nuclear fission takes place when the natural oscillation of a heavy nucleus causes it to break into two nuclei of similar mass. An example is the disintegration of americium-244 into iodine and molybdenum.

\[ ^{244}_{95}Am \rightarrow ^{134}_{53}I + ^{107}_{42}Mo + 3^1_0n \]
Fission does not happen the same way every time. The fission yield of uranium-235 mainly yields products close to $A=90$ and $A=130$ and relatively few nuclide corresponding to symmetric fission (close to 117) are formed.
Critical Mass: The minimum mass of fissionable particles that are needed to prohibit the majority of the neutrons from escaping thus sustaining a fission chain reaction.

- **Subcritical**: Does not sustain chain reactions.
- **Critical**: Sustains chain reactions.
- **Supercritical**: Sustains chain reactions and is hard to control.

Example Reaction:

\[
\frac{235}{92}U + \frac{1}{0}n \rightarrow \frac{141}{56}Ba + \frac{92}{36}Kr + 3\frac{1}{0}n
\]
Nuclear Energy

- **Little Boy**: Detonated by pushing two subcritical masses together to produce a supercritical mass.

- **Fat Man**: Detonated by imploding a single subcritical mass and using a strong neutron emitter to initiate the chain reaction.
Both nuclear weapons and nuclear power plants need uranium-235. Uranium-235 is the only isotope that is fissile with thermal neutrons.
Chapter 20: The Nucleus: A Chemist’s View

Nuclear Energy
Nuclear Energy

- Nuclear reactors undergo controlled chain reactions.
- Core is usually made out of $^{235}U$.
- Neutrons are slowed down by putting the core into a moderator.
- Control rods are made from neutron absorbing materials (usually B or Cd) that can be adjusted to control neutron numbers.
Nuclear Energy

Diagramming a disaster

The six reactors at the Fukushima Dai-ichi plant are boiling water reactors. In a typical commercial boiling water reactor, the reactor core creates heat. A steam-water mixture is produced when very pure water (reactor coolant) moves upward through the core absorbing heat. The steam-water mixture leaves the top of the core and enters the two stages of moisture separation. Water droplets are removed before the steam is allowed to enter the steam line. The steam line directs the steam to the main turbine, causing it to turn the turbine generator, which produces electricity.

Here is what happened at Unit 1 of the Fukushima Dai-ichi Nuclear Plant:

1. Tsunami knocked out power to the nuclear plant, crippling the system used to cool fuel rods.
2. Back-up generator didn’t work properly.
3. Pressure built up in the reactor vessel.
4. Pressure inside the reactor was reduced by venting steam.
5. The vented steam included hydrogen, which reacted with oxygen, either in the air or the cooling water, and caused the explosion of the building housing the reactor vessel.
6. Nuclear agency officials say Japan is injecting seawater into the core to avoid a meltdown.

SOURCES: U.S. Energy Information Administration; AP

UNIT 1
- Containment vessel
- Pressure vessel with fuel core
- Spent fuel pool
- Freshwater
- Suppression pool
- Spent fuel: 50 tons

AP
It can be seen that there is a large increase in nuclear binding energy per nucleon going from one lighter element to another. Consequently a large amount of energy is released when hydrogen nuclei fuse together to form nuclei of bigger elements.
Nuclear Energy

Fusion Reaction Scheme

\[ 4_1^1H \rightarrow 2_1^2H + 2_1^0e \]
\[ 2_1^2H + 2_1^1H \rightarrow 2_2^3He \]
\[ 2_2^3He \rightarrow 2_1^1H + 4_2^4He \]

Overall Reaction: \( 4_1^1H \rightarrow 2_1^0e + 4_2^4He \)

How much H is needed in g to generate \( 3 \times 10^{11} \) J?

Masses of Interest

\[ m_{2He}^4 = 4.0026 \ u \]
\[ m_{1e}^0 = 5.586 \times 10^{-4} \ u \]
\[ m_{1H}^1 = 1.0078 \ u \]
Student Question

How much would it cost to make 1 g of gold via the following process?

\[ ^{207}_{82}Pb \rightarrow ^{197}_{79}Au + 10^1_n + 3^0_e \]

Masses (u): 206.975997 196.9665687 1.008664 0.00054858

Helpful information: 1 kWhr = 3.6×10^6 J and the cost of electricity is $0.15 per kWhr

a) $1,499
b) $1.713×10^5
c) $2.953×10^5
d) None of the above
Take Away From Chapter 20

- **Big Idea:** Changes in the nucleus of an atom can result in the ejection of particles, the transformation of the atom into another element, and the release of energy.

- **Nuclear Decay** (1)
  - Know the three major decay pathways and the particles that they emit.
    - Alpha (α): $\text{^4}_2\text{He}$
    - Beta (β): $\text{^0}_{-1}\text{e}$
    - Gamma (γ): electromagnetic radiation
  - Be able to predict the product of nuclear decay (write balanced equations) for alpha decay, beta decay, positron decay, gamma, and electron capture. (6,7,9)
  - Be able to determine the most likely particle to be emitted knowing weather or not the nucleus is proton or neutron rich. (13)
Take Away From Chapter 20

- **Nuclear Radiation**
  - Know the uses of nuclear radiations (53)

- **Kinetics of Nuclear Decay**
  - Know the rate equation for nuclear processes
    - $Activity = kN$
  - Know how calculate the amount of particles after a given time. (17,18,19,29,34,77)
    - $ln(N) = -kt + ln(N_o)$
  - Know how to calculate the half life of a substance
    - $t_{1/2} = \frac{ln(2)}{k}$
  - Know how carbon dating works.

- **Nucleosythesis**
  - Know that nucleosythesis is the transmutation of elements into other elements

Numbers correspond to end of chapter questions.
Take Away From Chapter 20

- **Nuclear Energy**
  - Know that the energy released during a nuclear processes is dictated by Einstein's equation.\(^{(35,61)}\)
    - \(E = \Delta mc^2\)
  - Be able to calculate the nuclear binding energy of a substance.\(^{(37,41,80)}\)
    - Nuclear Binding Energy = \((m_{\text{atom}} - (#p (m_{1H}) + #n (m_n))) \cdot c^2\)
    - \(m_{0n} = 1.0087 \text{ u}\)
    - \(m_{1H} = 1.0078 \text{ u}\)
  - Know the difference between nuclear fission and fusion.\(^{(47)}\)
    - Fission: heavier atoms break apart
    - Fusion: small atoms combine to form larger atoms
  - Be able to calculate the energy released from fission or fusion.

Numbers correspond to end of chapter questions.