Year 12 Physics - Modern Physics

AS91172
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Contents

Chapter 1: Atoms and Isotopes

Learning Outcomes

- ☐ Define the terms proton, neutron, electron, nucleon, atomic mass, atomic number and isotope.

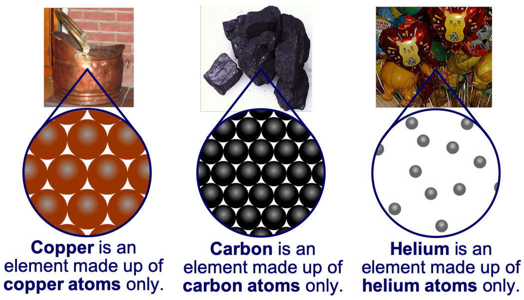
Aristotle and the Greeks in 450BC hypothesised that everything was made of water, earth, air and fire. Some years later, another Greek philosopher Democritus came up with the idea of an indivisible piece of matter - a fundamental building block. He did not know what it was, but theorised that one should exist. He called these pieces of matter *atomos (indivisible)*.

In the modern day we have a different theory that is testable and that allows us to make predictions. Our theory predicts that everything is made up of 119 different elements.

1.1 Atoms and Elements

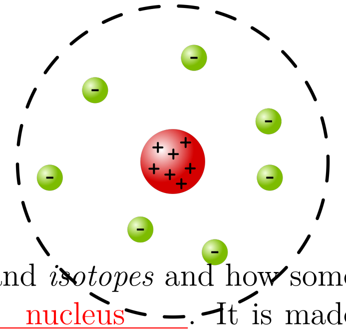
Pātai: What makes the elements different from each other?

They have distinct properties, but the thing that defines different elements is the number of protons in the nucleus. Every atom of the same element has the same number of protons.



1.1.1 Ngohe: Draw a labelled diagram of a lithium atom

1.1.2 The Rutherford Model



What you have drawn is the Rutherford Model of the atom. This model is the most common one we see in school today because it has very strong predictive powers. It is also very valuable because it allows to easily visualise things like *ions* and *isotopes* and how some chemical bonding works. The central region is called the nucleus. It is made of protons and neutrons which are strongly bound together by the nuclear force. Together we call protons and neutrons nucleons, as they exist in the nucleus. Electrons are constantly moving around the nucleus in a probabilistic way. This means that they do not have fixed orbits like the planets, but instead exist in a probability cloud. The size of the nucleus compared to the whole atom is very small, but it contains $> 99.95\%$ of the mass because electrons are very light. Protons have a positive charge, electrons have a negative charge, and neutrons have no change. Protons and electrons have an equal but opposite sized charge despite their very different masses.

1.2 Atomic and Mass Numbers

The number of protons in an atom (i.e. the atomic number) defines which type of atom it is. For example, and atom that has six protons MUST be a carbon atom, and cannot be any other.

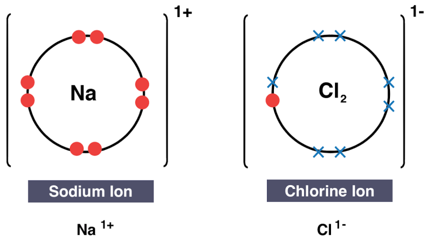
- **Atomic number**: The number of protons
- **Mass number**: The number of protons + neutrons

1.2.1 Ngohe: Reading the Periodic Table

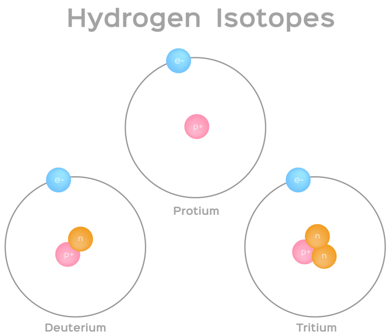
	Protons	Electrons	Neutrons	Nucleons	Atomic Number	Mass Number
Oxygen	8	8	8	16	8	
Sodium	11	11	12	23	11	
Aluminium	13	13	14	27	13	
Copper	29	29	35	64	29	

1.3 Ions

An atom is a neutral particle, having equal number of protons and electrons (recall: they have opposite but equal size electric charges). However, an atom may lose or gain one or more electrons during a reaction. This causes them to gain a *net charge*. When an atom has a charge it is called an ___ion___. Positively charged ions are called ___cations___ and negatively charged ions are called ___anions___.



1.4 Isotopes



An isotope is an atom with the same number of protons (same element), but with a different number of neutrons. This means that the *atomic number* is the same, but that the *mass number* is different.

This is why some periodic tables show a mass number with lots of decimal places, it is an average of the different isotopes.

Some isotopes are stable, while others like Carbon-14 is radioactive and will decay over time. Carbon-14 can be used to find the age of organic matter. They do this by looking at the ratio of Carbon-14 compared to the other isotopes.

1.4.1 Ngohe: Carbon Isotopes

For Carbon-12, Carbon-13 and Carbon-14, complete the table below.

	Protons	Electrons	Neutrons	Nucleons	Atomic Number	Mass Number
Carbon-12						
Carbon-13						
Carbon-14						

1.5 Whakawai: Atomic Structure

Atoms are made of a central dense part called the ___nucleus___ surrounded by a moving cloud of ___electrons___. The particles in the central region are called nucleons and are either protons or ___neutrons___. The charge on protons is ___positive___.

The nucleons are attracted strongly to each other by a force called the ___nuclear___ force. The protons however, repel each other, because they have similar charges. This repulsion force between the protons is an ____electrostatic____ force. As a result of these forces in the nucleus, most nuclei are stable. However, if nuclei are disrupted by nuclear reactions enormous amounts of ____energy____ may be released. The reason for this is that the ____forces____ in the nucleus are very strong.

The atomic number is the number of ____protons____ in the nucleus of an atom. The mass number is the number of ____protons____ and ____neutrons____ in the nucleus of an atom. Isotopes of an element will always have the same ____atomic____ number but different ____mass____ numbers.

State the number of protons and neutrons in the following nuclides.

1. ${}^{222}_{86}Rn$: 86 protons, 136 neutrons

2. ${}^{238}_{92}U$: 92 protons, 146 neutrons

3. ${}^{63}_{29}Cu$: 29 protons, 34 neutrons

4. ${}^{27}_{13}Al$: 13 protons, 14 neutrons

Write the following nuclides in their symbol form.

1. A nucleus of carbon with 6 protons and 8 neutrons.
   ${}^{14}_{6}C$

2. A nucleus of sulfur with 16 protons and 17 neutrons.
   ${}^{33}_{16}S$

3. A nucleus of helium with 2 neutrons.
   ${}^{4}_{2}He$

4. A nucleus of hydrogen with no neutrons.
   ${}^{1}_{1}H$

5. A nucleus of nitrogen with a mass number of 16.
   ${}^{16}_{7}N$

6. A nucleus of potassium with 20 neutrons.
   ${}^{20}_{39}K$

7. A nucleus of an atom with 56 protons and 84 neutrons.
   ${}^{140}_{84}Po$

Chapter 2: Atomic Structure

Learning Outcomes

- ☐ Understand the history and process of how we formulated the current atomic model

Introductory Video: https://youtu.be/xazQRcSCRaY

2.1 The Greeks

As mentioned earlier, Aristotle and the Greeks in 450BC thought that everything was made of water, earth, air and fire. Some years later, another Greek philosopher Democritus came up with the idea of some indivisible piece of matter - a fundamental building block. He did not know what it was, but theorised that one should exist. He called these pieces of matter *atomos (Latin: indivisible).*

2.2 John Dalton (1766 - 1844)

John Dalton was an English chemist who introduced *atomic theory* into chemistry. There is some debate about where he got his theory, but the main points he developed were:

- Elements are made of extremely small particles called atoms
- Atoms of a given element are identical in size, mass and other properties
- Atoms cannot be subdivided, created or destroyed
- Atoms of different elements combine in simple whole-number ratios to form chemical compounds. E.g. $MgCl_c$.
- In chemical reactions, atoms are combined, separated or rearranged

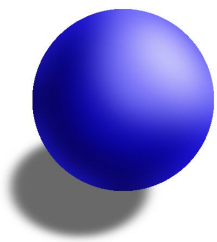


Figure 2.1: Dalton's ball theory of the atom.

He was not able to ascertain the weight of any elements, but did attempt to order them by *relative weight*. It was with John Dalton when *atomos* from the Greeks became *atoms*.

2.3 Joseph Thomson (1856–1940)

Joseph Thomson was a British physicist who did a lot of work with cathode rays (<u>streams of electrons</u>) and who was awarded the Nobel Laureate in Physics for discovering the electron. This was the first subatomic particle to be discovered! He is also credited with finding the first scientific evidence of <u>isotopes</u>.

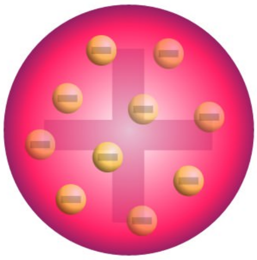


Figure 2.2: Thomson's Plum Pudding theory of the atom.

At the time of his research they were not originally aware that cathode rays were streams of "electrons". He only knew that they were negatively charged and had <u>a very small mass</u>. He hypothesised that the electrons were emitted from the atoms inside the cathode ray tube, and thus concluded <u>that atoms were in fact divisible</u>.

If the electrons were inside the atoms, and an atom was neutral, the electrons would have to be evenly distributed throughout, and the atom itself made of some positive material.

2.4 Ernest Rutherford (1871-1937)

Ernest Rutherford is a New Zealand-born British Physicist credited as the father of nuclear physics. He was the discoverer of the concept of <u>radioactive half-life</u>, and was awarded the Nobel Prize in Chemistry for his work into the disintegration of the elements (<u>radioactivity</u>).

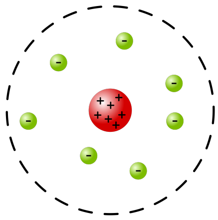


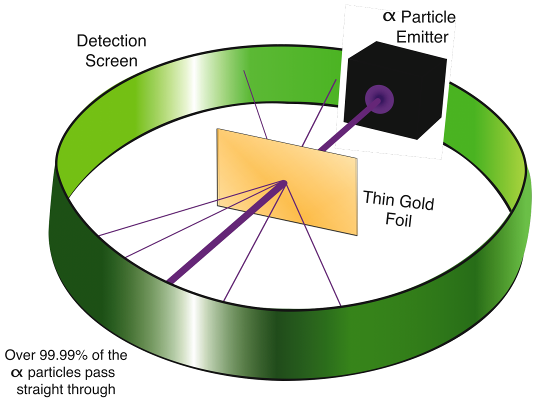
Figure 2.3: Rutherford's Model of the Atom

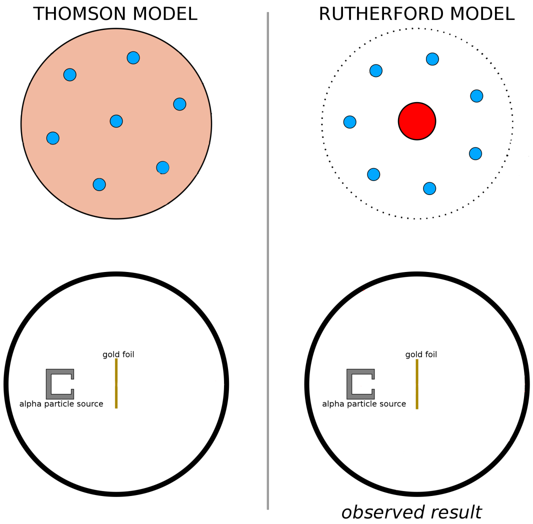
His work on the atom revolved around something called <u>The Gold Foil Experiment</u> where he fired alpha particles (<u>helium nuclei</u>) at a sheet of thin gold foil. By analysing the scatter pattern of the alpha particles he was able to determine that there is a positive nucleus in the centre of the atom, and that the electrons should orbit around the outside.

Notice that at this point we still have not discovered the neutron.

2.5 The Gold Foil Experiment

Introductory Video: https://www.youtube.com/watch?v=1EdTw4I6L0U





- **Observation 1**: Most alpha particles were found to go straight through the foil.
  Conclusion:

- **Observation**: Some alpha particles experienced a small angle of deflection.
  Conclusion:

- **Observation 3**: Very few alpha particles were deflected.
  Conclusion:

- **Observation 4**: Some particles were deflected at a very large angle.
  Conclusion:

- Explain why the gold foil experiment had to be carried out in a vacuum.

- Explain why it was necessary for the gold foil to be a few atoms thick.

Chapter 3: Nuclear Decay

Learning Outcomes

- ☐ Describe alpha radioactive decay
- ☐ Describe beta radioactive decay
- ☐ Describe gamma radioactive decay

Introductory Video: https://youtu.be/UtZw9jfIxXM

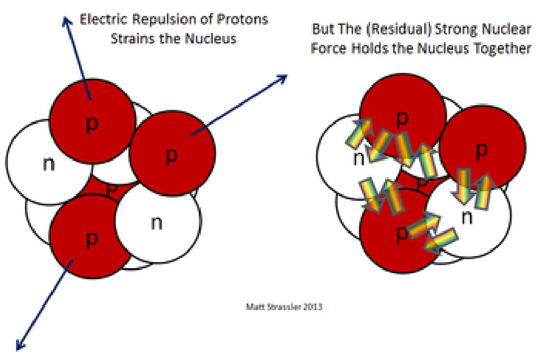
3.1 Pātai: What is a nuclear reaction?

- It **is not** a physical reaction (e.g. changing state)
- It **is not** a chemical reaction (e.g. forming ionic compounds)
- It **is** a reaction where: the nucleus of an atom changes

There are three types of nuclear reactions that we are interested in for this topic:

- **Radioactive Decay (alpha, beta, gamma)**
- Nuclear Fission
- Nuclear Fusion

3.2 Why Nuclear Decay Occurs



Inside the nucleus are the protons and neutrons. The neutrons do not carry an electric charge, so do not interact electrically. The protons, however, carry a positive charge. We know that like charges repel, so *why does the nuclear not fall apart?*

It turns out that when nucleons get close enough another force comes into effect: the ____strong nuclear force____. This force glues the nucleons together. Nuclear decay occurs when the nucleus gets very large; either by having a large atomic number, or by being an isotope with a large number of neutrons.

Adding nucleons increases the volume of the nucleus, and thereby diluting the strong nuclear force. When the strong nuclear force is diluted such that the electrostatic force is now larger, the nucleus ____may split apart____. This is called radioactive decay!

Recall the Law of Conservation of Energy. Similar laws apply to nuclear equations and these four properties are also conserved:

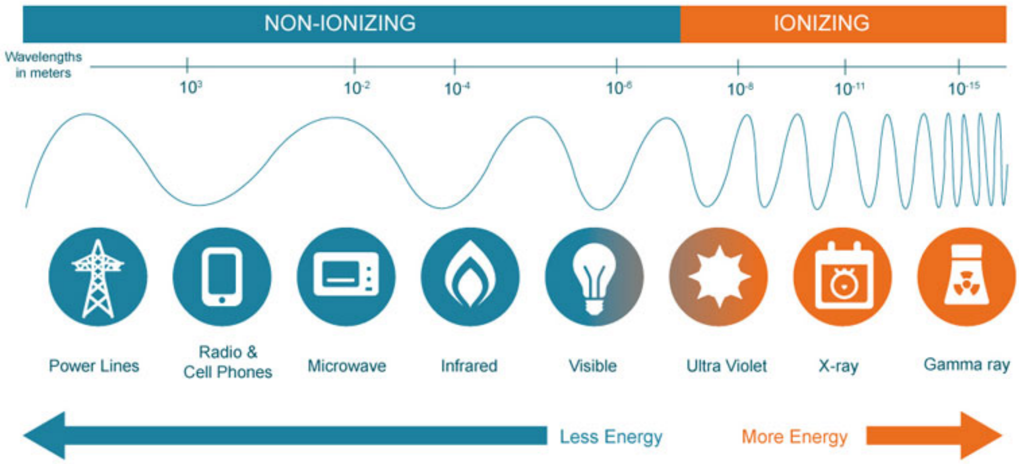
- Energy
- Momentum (linear and angular)
- Electric and Magnetic Charge
- Nucleon (mass) Number

Video: https://www.youtube.com/watch?v=TJgc28csgV0

3.3 Ionizing Radiation

Ionising means to have the ability to strip electrons from an atom/molecule. In some circumstances this can cause bonds to break - this can be bad in regards to cells and DNA. Heavy atoms like α particles may also simply break a molecule on impact (think $p = mv$).

The ability to ionize is also characterised by having an electric charge. Neutral particles are less ionising. Low energy electromagnetic radiation is also not ionising. This is why your phone or microwave cannot harm you, but repeated x-rays can.



3.4 Alpha Decay

During alpha (α) decay a particle is emitted from the nucleus. This particle is a helium nuclei, also known as an alpha particle $^4_2He^{2+}$. It is positively charged because it contains just two neutrons and two protons. It is slow moving (up to 10% the speed of light) due to its relatively large mass. Its large mass means it can only move a few cm through the atmosphere before being absorbed or *redirected*. It also means that it is easy to protect against. Conversely, the large mass

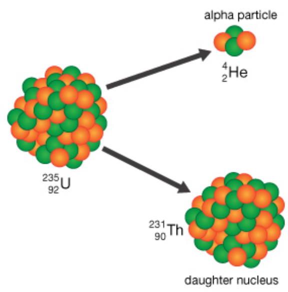


Figure 3.1: Alpha decay of a U-235 nucleus.

(high momentum) means that it will do a lot of damage if it impacts organic matter like DNA. It is said to have the greatest ionising ability

The majority of alpha emitters are the elements with atomic number greater than 83, although some other smaller nuclei also undergoing alpha emission.

3.5 Beta Decay

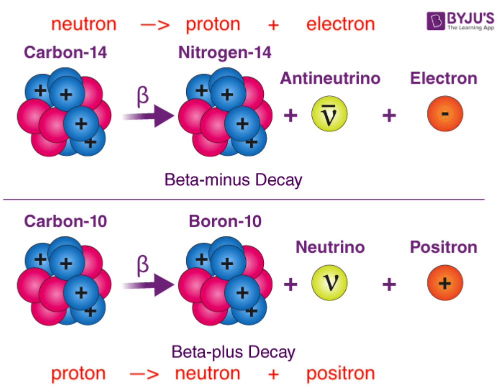


Figure 3.2: The two types of beta decay.

During beta (β^{-1}) decay a neutron inside the nucleus changes (decays) into a proton and a high energy electron is emitted. This changing of a neutron to a proton increases the atomic number of the atom by one, and therefore changes the element!

The emitted high-energy electron can travel up to 90% the speed of light due to its very small mass, and has a medium range in the atmosphere (approximately 30cm). It is able to pass through a sheet of paper but will be stopped by a more dense material e.g. 5mm of aluminium. It is said to have medium ionising ability and can disrupt chemical bonding on impact.

Notice how there are two options for beta decay in the diagram to the right. **In both cases electric charge is conserved**.

3.6 Gamma Decay

Gamma (γ) radiation is a form of high-energy electromagnetic radiation, and is not a particle at all. It is instead an electromagnetic wave with an extremely high frequency. This kind of radiation occurs when a nucleus is left in an *excited state* after undergoing alpha or beta decay. It is a way for the nucleus to release energy.

Due to being electromagnetic radiation, it travels at the speed of light and will travel through large volumes of atmosphere. It requires several centimetres of dense metal (e.g. lead) to block gamma radiation, and due to its lack of mass, has very little ionising ability.

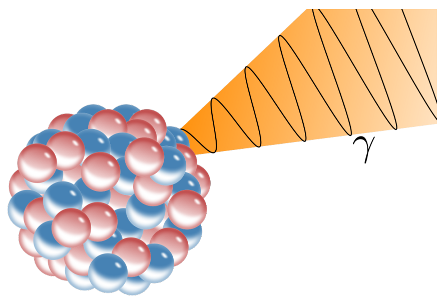
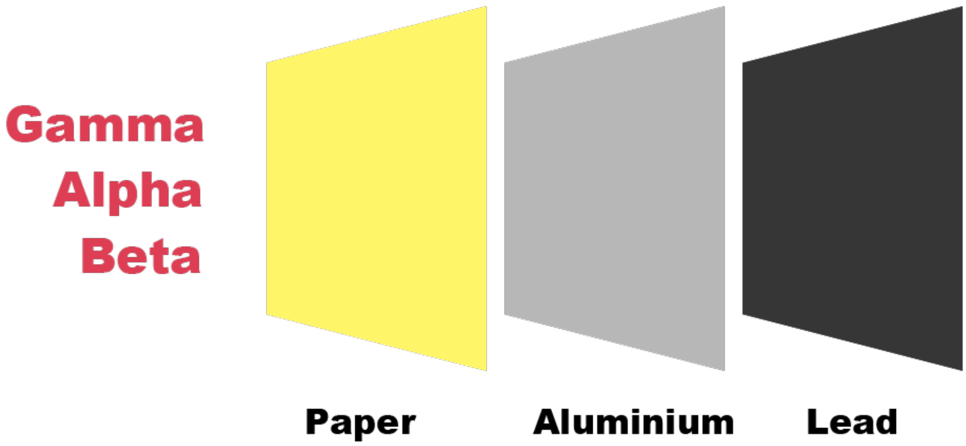


Figure 3.3: Notice that the nucleus stays the same.

3.7 Ngohe: Radiation Protection

Draw an arrow from each type of radiation, stopping the arrow at the material that is capable of blocking it.



3.8 Whakawai: Types of Radiation

Summarise the types of radiation below.

	Mass	Charge	Speed	Ionising Ability
Alpha Particle				
Beta Particle				
Gamma Ray				

1. State which elements tend to be naturally radioactive and explain why.
   Elements with very large nuclei tend to be radioactive. This is because the strength of the strong nuclear force is diluted due to the large volume of the nucleus. This means that the electrostatic repulsion of the protons can overcome the strong nuclear force and break apart the nucleus.

2. Identify which of the three types of radiation is being described below.

   (a) It travels a few cm in air.
   Alpha radiation

(b) It will pass through aluminium sheet but is stopped by a few mm of lead.
Beta radiation

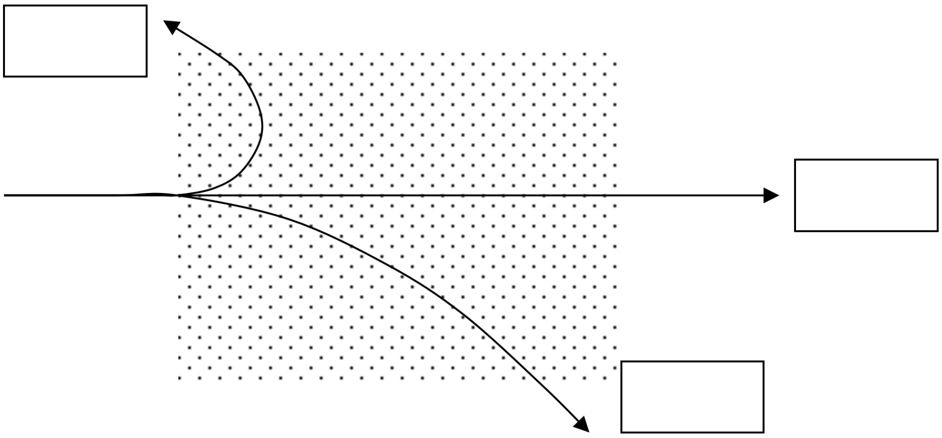
(c) It is stopped by a sheet of paper.
Alpha radiation

(d) It will pass through more than a few mm of lead.
Gamma radiation

(e) It is highly ionising.
Alpha radiation

(f) It is not deflected by a magnetic field.
Gamma radiation

3. When the three types of radiation are passed through a magnetic field they separate into three beams as shown. Identify which beam is which.



4. Describe what happens to the atomic number and mass number of a nucleus which emits a beta particle.
When a beta particle (high speed electron) is emitted, a neutron must have transformed into a proton and emitted the electron. This means the mass number is unchanged, but the atomic number has decreased by one.

Chapter 4: Nuclear Equations

Learning Outcomes

- ☐ Balance nuclear equations using the knowledge of the conservation of atomic and mass numbers.

An equation for a nuclear reaction looks a lot like a regular chemical reaction. The reactants go on the left, and the products (daughter products) go on the right. We also use an arrow in the middle. The main change is that we indicate the mass an atomic numbers to the left of each atom. M represents the ____mass number____, A represents the ____atomic number____ and X represents ____the symbol for the atom____.

$$^{M}_{A}X$$

Pātai: In the space provided write the nuclear symbols for Thorium, Plutonium, Americium and Gold.

4.1 Alpha Decay

In alpha (α) decay a helium nucleus is emitted from the parent atom. This means that the atom loses two protons and two neutrons. This means that the atomic number ____decreases____ by ____two____, and the mass number ____decreases____ by ____two____.

Pātai: Write the nuclear symbol for an alpha particle (two options):

Pātai: Use your knowledge of alpha decay to predict what atom would be produced.

	Before	**After**
Atom	Thallium-214	
Number of Protons		
Number of Neutrons		
Atomic Number		
Mass Number		

Pātai: Next, we should attempt to write this decay as a nuclear equation where Thallium-214 is the reactant, and the daughter atom and alpha particle are the products.

4.2 Beta Decay

In beta (β^{-1}, e^{-1}) decay a single neutron turns into a proton and a ___high speed electron___ is emitted. This means that the atomic number ___increases___ by ___one___, and the mass number ___stays the same___.

Pātai: Write the nuclear symbol for a beta particle (two options):

Pātai: Use your knowledge of beta decay to predict what atom would be produced:

	Before	**After**
Atom	Polonium-218	
Number of Protons		
Number of Neutrons		
Atomic Number		
Mass Number		

Pātai: Next we should attempt to write this decay as a nuclear equation where Polonium-218 is the reactant, and the daughter atom and beta particle are the products.

4.3 Positron Emission

Due to the symmetrical nature of Physics, each particle has an *antiparticle*. In this case, this means that *electrical charge can be conserved* if the opposite of beta decay occurs. This means that a single proton turns into a neutron and emits a positron (think: a positive electron). This means that the atomic number ___decreases___ by ___one___, and the mass number stays the same.

Pātai: Write the nuclear symbol for a positron (two options):

Pātai: An example atom that undergoes positron decay is Magnesium-23. Use your knowledge of beta decay to predict what atom would be produced:

Pātai: Next we should attempt to write this decay as a nuclear equation where Magnesium-23 is the reactant, and the daughter atom and positron are the products.

	Before	After
Atom	Magnesium-23	
Number of Protons		
Number of Neutrons		
Atomic Number		
Mass Number		

4.4 Gamma Decay

In gamma (γ) decay an excited nucleus emits high-energy electromagnetic waves in the form of gamma radiation. The nucleus does not emit any particles - it only becomes more *relaxed*. This means that the atomic and mass numbers stay the same.
Pātai: Write the nuclear symbol for a gamma ray (one option):

Pātai: An example of gamma decay is after Cobolt-60 has decayed to Nickel-60 via beta decay. The Nickel-60 atom is in an excited (high energy state) and needs to emit some energy. Use your knowledge of gamma decay to predict what atom would be produced:

	Before	After
Atom	Nickel-60	
Number of Protons		
Number of Neutrons		
Atomic Number		
Mass Number		

Pātai: Next we should attempt to write this decay as a nuclear equation where Nickel-60 is the reactant, and the daughter atom and gamma ray are the products.

4.5 Whakawai: Decay Equations

Write the nuclear equations for these reactions. You may choose to write one or two equations in the case of double decays or absorptions.

1. An alpha decay of Polonium-218

2. A beta decay of Hydrogen-3

3. A gamma decay of Carbon-14

4. An absorption of a neutron by Carbon-13

5. A double alpha decay of Uranium-234

6. A double beta decay of Thorium-234

4.6 Whakawai: Types of Radiation

Complete the two nuclear equations below with appropriate symbols and numbers to identify the type of radiation emitted.

1. $^{90}_{38}Sr \rightarrow ^{90}_{39}Y + ...$ Name of Radiation:

2. $^{60}_{27}Co \rightarrow ^{60}_{27}Co + ...$ Name of Radiation:

3. Uranium-238 decays to thorium (Th) by emitting an alpha particle. Complete the equation for this reaction using appropriate symbols and numbers.

   $^{238}_{92}U \rightarrow$

4. What is meant by the term *ionising*?

5. Which type of radiation is most strongly ionising?

6. An electron can be emitted from a radioactive nucleus even though it cannot exist inside the nucleus. Where does that electron come from?

7. As part of an experiment, Rutherford placed an alpha particle emitter into a jar. When the jar was later tested it contained the gas helium that was not previously present. Explain how the helium was formed.

8. The isotope Radon-222 ($^{222}_{86}Rn$) undergoes two consecutive radioactive decays and turns into the isotope Polonium-218 ($^{218}_{84}Po$). Write equations to determine the TWO separate emissions. Name the emissions.

Chapter 5: Half-Life

Learning Outcomes

- ☐ Be able to make half-life graphs
- ☐ Be able to interpret half-life graphs

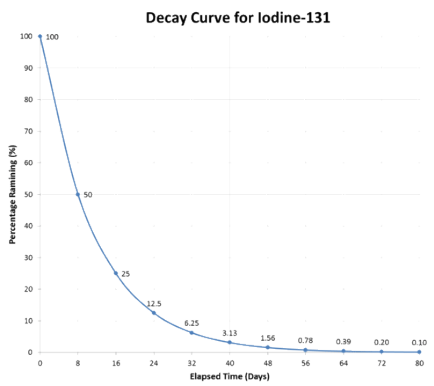
Introductory Video: https://www.youtube.com/watch?v=zXw2cOSBB8E

5.1 Whakamātau: Dice

1. In pairs, collect a container of dice from the front.
2. Count and record the total number of dice.
3. Roll all the dice in one go. Discard aside the dice with dots facing up, count the dice without dots and record that value.
4. Roll all the dice in one go that did did not land with dots facing up. Discard those with dots facing up, count, record and repeat until no dice remain.
5. Create a line graph showing the number of dice rolled (y-axis) vs the roll number (x-axis).

What you have hopefully discovered is an exponential decay curve! This type of curve can be observed in a multitude of places in nature, but in Nuclear Physics it shows the half-life of a particular radioactive atom.

It is important to note that *for any section of a decay curve, it is steeper on the left and more gentle on the right.* This means that the mass/number of atoms is changing more rapidly on the left.



5.2 What is Half-Life?

Definition: The time taken for half of a radioactive sample to undergo decay.

Many things in the universe are deterministic - calculations can be performed to make accurate and specific predictions, however we are unable to predict when *exactly* a particular radioactive nuclei will decay. It turns out that decay is *probabilistic* and it is impossible to make a prediction for a single nuclei.

It is, however, possible to make predictions about groups of atoms using statistics (exponential decay curves).

We should also note that each different radioactive nuclei has a different half-life. Tellurium-128 is believed to have a half-life of over 128 trillion years, while Hydrogen-7 has a half-life of $23 \times 10^{-24}s$.

Pātai: If there were initially 1200 particles in a sample, fill out the number of particles left *after* each half life has elapsed.

	Remaining		
Half-Lives Elapsed	**Fraction**	**Percentage**	**Particles**
1			
2			
3			
4			
5			
6			
7			

5.3 Half-Life Calculations

Those of who are confident with their math skills will have noticed that you can formulate an equation to help you make precise predictions about the number of particles left for any given time. In Year 12 Physics we do not use a formula, rather we make more approximate predictions by creating and reading graphs. Equation use is something you may see in Year 13 and into tertiary education. We can also perform predictions simply by *dividing by two* (as above) and using this to help us make estimates.

5.3.1 Method 1: Dividing

This method is slightly less accurate in some cases than the graphical method. The half-life of Hydrogen-3 (Tritium) is approximately 12.25 years. If you found a small sample of Tritium containing 5,000,000 un-decayed nuclei.

1. How many nuclei will be left after 12.25 years?

2. How many nuclei will be left after 24.5 years?

3. How many nuclei will be left after 49 years?

4. How many nuclei will be left after 196 years?

5. How long until there is less than 2500 un-decayed nuclei left?

5.3.2 Method 2: Graphs

This method can help us gain a better view when we want to know about non-integer half-lives e.g. the number of particles after 4.5 half-lives.
Pātai: You found a $50g$ sample of Cobalt-60 which has a half-life of 5 years.

1. Sketch a mass vs. time graph of the Cobalt-60 sample over a 30-year period. Use the graph to answer the following questions:

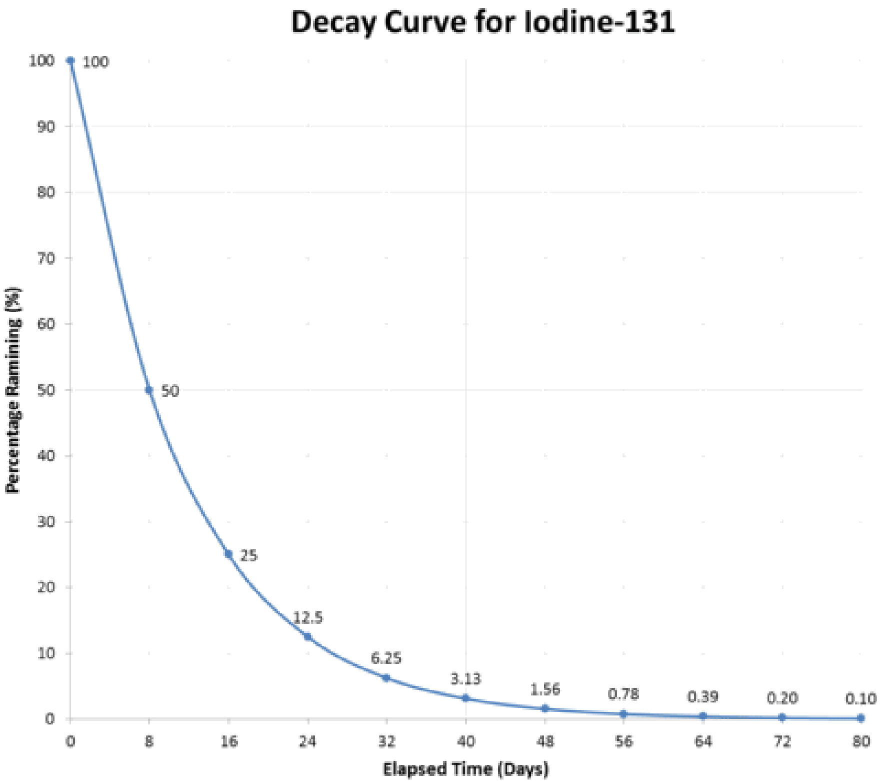
2. How long it would take for the mass of the $50g$ sample to fall just below $1.17g$.

3. Estimate the mass of Cobalt-60 left after 12.5 years.

4. Estimate the number of Cobalt-60 particles after 20 years.

5.3.3 Whakawai: Iodine-131

Predict the amount of time until there is 37.5% of the original sample of Iodine-131 left.



5.3.4 Whakawai: Carbon-Dating

Radio-carbon dating is used to estimate the age of objects that were once living. All living things contain a small amount of radioactive Carbon-14 ($^{14}_{6}C$). Radioactive C-14 is created through the impact of cosimic rays with carbon in the atmosphere. This carbon is then used by plants in photosynthesis, and these plants eaten by animals.

Organisms have a relatively constant ratio of C-14 in them over their lifetime due to them continually consuming it through food. Once they die they are no long acquiring C-14 and it starts to decay away.

Carbon-14, which has a half-life of 5700 years, decays to Carbon-12. By measuring the activity of a sample of dead tissue, its approximate age can be determined. Activity is measured in counts per minute ($\frac{counts}{min}$ or $\frac{decays}{minute}$).

1. Calculate the number of neutrons present in a carbon 14 nucleus.

2. State what is meant by the term *half-life*.

3. A sample of living wood has an activity of $16 counts/min$ per gram. Calculate the activity of a $20g$ sample of living wood.

4. Hence calculate the activity of a $20g$ sample of wood from a tree that died 17,100 years ago. State the correct unit for your answer.

5. A $5.0g$ sample of old wood from an archaeological site has an activity of $20 counts/min$. Calculate the activity of the sample when the wood was living, and hence calculate how long ago the tree died.

Chapter 6: Fission and Fusion

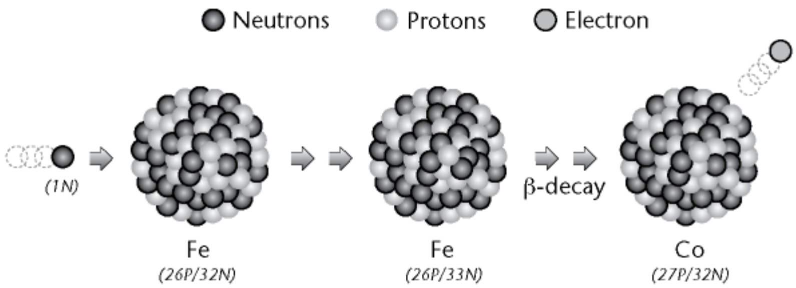
Learning Outcomes

- ☐ Understand the difference between nuclear fission and fusion
- ☐ Use $E = mc^2$
- ☐ Use $P = \frac{E}{t}$

Introductory Video: https://www.youtube.com/watch?v=rcOFV4y5z8c

6.1 Nuclear Fission

Recall from earlier that nuclei are generally stable because the ____strong nuclear force____ is greater than the ____electrostatic force____. This means that even though the protons repel each other, the nucleus does not break apart. Also recall that atoms with a nucleus that is too large in volume can be unstable (radioactive). This is because the electrostatic force is greater than the strong nuclear force, and the atom can then break down (decay) via alpha or beta/position emission.



By accelerating neutrons to a high speed and colliding them with an already large nucleus, the neutron can sometimes be incorporated into the nucleus via the ____strong nuclear force____. This in turn causes the electrostatic force to now become larger than the strong nuclear force and **the nuclei to break apart in nuclear fission**. This is the process through which nuclear reactors produce energy here on Earth.

6.1.1 Pātai: Fission of Uranium

Uranium-235 is bombarded with a high speed neutron. The resulting nucleus becomes radioactive and decays into two daughter nuclei: Krypton-92 and Barium-141.

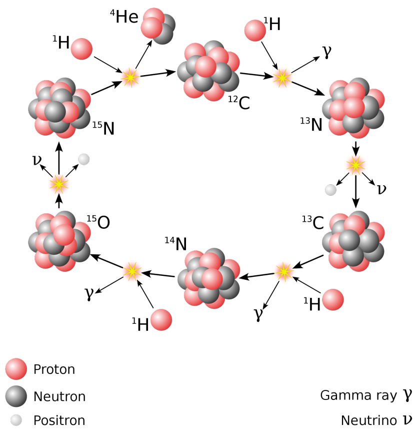
1. Write a nuclear equation describing the bombardment and fission of U-235

2. What is the third product? How did you determine it - what was conserved?

6.2 Nuclear Fusion

Unlike Nuclear Fission, with fusion we can add whole nuclei together! This is the process through which stars produce energy. Fusion typically requires very high temperatures and pressures in order to get the nuclei close enough to combine. It is for this reason that we struggle to create self-sustaining fusion reactions here on Earth - it is hard to create and maintain these conditions.

However, it is important to note that fusing nuclei smaller than iron produces energy, while trying to fuse nuclei larger than iron requires more energy than is produced. We will see this concept again later!



6.2.1 Pātai: Fusion of Hydrogen

In the Sun deuterium (H-2) and tritium (H-3) are fused together to create helium (He-4) and one other product.

1. Write a nuclear equation describing the fusion of H-2 and H-3

2. What is the second product? How did you determine it - what was conserved?

6.3 Mass-Energy Equivalence

You probably know Einstein's most famous formula were E is energy, m is mass and c is the speed of light:

$$E = mc^2$$

Because the speed of light is so large, this implies that a small amount of mass can be converted into a large amount of energy.

6.3.1 Pātai: Antimatter

Let's pretend $2g$ of material is converted directly into energy (this would be a matter-antimatter collision). Calculate the amount of energy generated by this reaction, given $c \approx 3 \times 10^8 ms^{-1}$.

Knowns:

Unknowns:

Formula:

Substitute:

Solve + Unit:

Introductory Video: https://www.youtube.com/watch?v=HEYbgyL5n1g

6.4 How Fission and Fusion Produce Energy

It turns out that if you measure the mass of the reactants and products of a nuclear reaction, mass is not (exactly) conserved. Instead, the products have slightly less total mass than the reactants. This means that some mass was lost. Where did it go? It turned into energy via mass-energy equivalence.

6.4.1 Pātai: Fusion of Deuterium

Introductory Video: https://www.youtube.com/watch?v=mZsaaturR6E

$$^3_1H + ^2_1H \rightarrow ^4_2He + ^1_0n$$

- Tritium (^3_1H) $= 5.00641 \times 10^{-27} kg$
- Deuterium (^2_1H) $= 3.3436 \times 10^{-27} kg$
- Helium (^4_2He) $= 6.64466 \times 10^{-27} kg$
- Neutron (^1_0n) $= 1.67493 \times 10^{-27} kg$

Use these data to answer the following questions.

1. Calculate the total mass of the reactants.

2. Calculate the total mass of the products.

3. Calculate the amount of mass lost during the reaction.

4. Calculate the energy produced during this reaction.

5. Calculate the power output of this reaction if it took $0.0001s$ to occur ($P = \frac{E}{t}$).

6.4.2 Pātai: Fission of U235

A nuclear power plant in the US can produce $1GW$ of power through neutron bombardment of U-235 and consequently, its fission. This fission produces Ba-141, Kr-92 and three neutrons.

- $U - 235 = 390.2480 \times 10^{-27} kg$
- $Ba - 141 = 233.9616 \times 10^{-27} kg$
- $Kr - 92 = 152.5794 \times 10^{-27} kg$
- $Neutron = 1.67493 \times 10^{-27} kg$

Use these data to answer the following questions.

1. Write an equation describing this nuclear reaction.

2. Calculate the total mass of the reactants.

3. Calculate the total mass of the products.

4. Calculate the amount of mass lost during the reaction.

5. Calculate the energy produced during this reaction.

6. If the plant is running for one year, calculate the mass of U-235 required. Start by calculating the amount of mass needed to produce $1GW$ of power, and then scale that up to the length of one year.

PERIODIC TABLE OF THE ELEMENTS

Key (example: Gold):

- Group (IUPAC): 11
- Group (CAS): IB
- Atomic Number: 79
- Symbol: Au
- Name: Gold
- Atomic Mass: 196.967
- Electron Shell Configuration: 2 8 18 32 18 1
- Oxidation States: +3 +1

ELECTRON SHELLS

Energy Level	1	2	3	4	5	6	7	8
Shell Name	K	L	M	N	O	P	Q	R
Max. Electrons	2	8	18	32	32	18	8	2
s	2	2	2	2	2	2	2	2
p		6	6	6	6	6	6	
d			10	10	10	10		
f				14	14			

Period	Group	Atomic Number	Symbol	Name	Atomic Mass	Electron Shell Configuration	Oxidation States
1	1 IA	1	H	Hydrogen	1.008	1	+1 -1
1	18 VIIIA	2	He	Helium	4.003	2	0
2	1 IA	3	Li	Lithium	6.941	2 1	+1
2	2 IIA	4	Be	Beryllium	9.012	2 2	+2
2	13 IIIA	5	B	Boron	10.811	2 3	+3
2	14 IVA	6	C	Carbon	12.011	2 4	+4 +2 -4
2	15 VA	7	N	Nitrogen	14.007	2 5	+5 +3 -3
2	16 VIA	8	O	Oxygen	15.999	2 6	-2
2	17 VIIA	9	F	Fluorine	18.998	2 7	-1
2	18 VIIIA	10	Ne	Neon	20.180	2 8	0
3	1 IA	11	Na	Sodium	22.990	2 8 1	+1
3	2 IIA	12	Mg	Magnesium	24.305	2 8 2	+2
3	13 IIIA	13	Al	Aluminum	26.982	2 8 3	+3
3	14 IVA	14	Si	Silicon	28.086	2 8 4	+4 -4
3	15 VA	15	P	Phosphorus	30.974	2 8 5	+5 +3 -3
3	16 VIA	16	S	Sulfur	32.066	2 8 6	+6 +4 +2 -2
3	17 VIIA	17	Cl	Chlorine	35.453	2 8 7	+7 +5 +3 +1 -1
3	18 VIIIA	18	Ar	Argon	39.948	2 8 8	0
4	1 IA	19	K	Potassium	39.098	2 8 8 1	+1
4	2 IIA	20	Ca	Calcium	40.078	2 8 8 2	+2
4	3 IIIB	21	Sc	Scandium	44.956	2 8 9 2	+3
4	4 IVB	22	Ti	Titanium	47.867	2 8 10 2	+4
4	5 VB	23	V	Vanadium	50.942	2 8 11 2	+5
4	6 VIB	24	Cr	Chromium	51.996	2 8 13 1	+6 +3
4	7 VIIB	25	Mn	Manganese	54.938	2 8 13 2	+7 +4 +2
4	8 VIIIB	26	Fe	Iron	55.845	2 8 14 2	+6 +3 +2
4	9 VIIIB	27	Co	Cobalt	58.933	2 8 15 2	+2
4	10 VIIIB	28	Ni	Nickel	58.693	2 8 16 2	+2
4	11 IB	29	Cu	Copper	63.546	2 8 18 1	+2 +1
4	12 IIB	30	Zn	Zinc	65.38	2 8 18 2	+2
4	13 IIIA	31	Ga	Gallium	69.723	2 8 18 3	+3
4	14 IVA	32	Ge	Germanium	72.631	2 8 18 4	+4 +2 -4
4	15 VA	33	As	Arsenic	74.922	2 8 18 5	+5 +3 -3
4	16 VIA	34	Se	Selenium	78.971	2 8 18 6	+6 +4 +2 -2
4	17 VIIA	35	Br	Bromine	79.904	2 8 18 7	+5 +3 +1 -1
4	18 VIIIA	36	Kr	Krypton	83.798	2 8 18 8	+2 0
5	1 IA	37	Rb	Rubidium	85.468	2 8 18 8 1	+1
5	2 IIA	38	Sr	Strontium	87.62	2 8 18 8 2	+2
5	3 IIIB	39	Y	Yttrium	88.906	2 8 18 9 2	+3
5	4 IVB	40	Zr	Zirconium	91.224	2 8 18 10 2	+4
5	5 VB	41	Nb	Niobium	92.906	2 8 18 12 1	+5
5	6 VIB	42	Mo	Molybdenum	95.95	2 8 18 13 1	+6 +4
5	7 VIIB	43	Tc	Technetium	98.907	2 8 18 13 2	+7 +4
5	8 VIIIB	44	Ru	Ruthenium	101.07	2 8 18 15 1	+4 +3
5	9 VIIIB	45	Rh	Rhodium	102.906	2 8 18 16 1	+3
5	10 VIIIB	46	Pd	Palladium	106.42	2 8 18 18	+4 +2
5	11 IB	47	Ag	Silver	107.868	2 8 18 18 1	+3 +2 +1
5	12 IIB	48	Cd	Cadmium	112.414	2 8 18 18 2	+2
5	13 IIIA	49	In	Indium	114.818	2 8 18 18 3	+3
5	14 IVA	50	Sn	Tin	118.711	2 8 18 18 4	+4 +2 -4
5	15 VA	51	Sb	Antimony	121.760	2 8 18 18 5	+5 +3 -3
5	16 VIA	52	Te	Tellurium	127.6	2 8 18 18 6	+6 +4 +2 -2
5	17 VIIA	53	I	Iodine	126.904	2 8 18 18 7	+7 +5 +3 +1 -1
5	18 VIIIA	54	Xe	Xenon	131.293	2 8 18 18 8	+6 +4 +2 0
6	1 IA	55	Cs	Cesium	132.905	2 8 18 18 8 1	+1
6	2 IIA	56	Ba	Barium	137.328	2 8 18 18 8 2	+2
6	3 IIIB	57-71		Lanthanoids			
6	4 IVB	72	Hf	Hafnium	178.49	2 8 18 32 10 2	+4
6	5 VB	73	Ta	Tantalum	180.948	2 8 18 32 11 2	+5
6	6 VIB	74	W	Tungsten	183.84	2 8 18 32 12 2	+6 +4
6	7 VIIB	75	Re	Rhenium	186.207	2 8 18 32 13 2	+4
6	8 VIIIB	76	Os	Osmium	190.23	2 8 18 32 14 2	+4
6	9 VIIIB	77	Ir	Iridium	192.217	2 8 18 32 15 2	+4 +3
6	10 VIIIB	78	Pt	Platinum	195.085	2 8 18 32 17 1	+4 +2
6	11 IB	79	Au	Gold	196.967	2 8 18 32 18 1	+3 +1
6	12 IIB	80	Hg	Mercury	200.592	2 8 18 32 18 2	+2 +1
6	13 IIIA	81	Tl	Thallium	204.383	2 8 18 32 18 3	+3 +1
6	14 IVA	82	Pb	Lead	207.2	2 8 18 32 18 4	+4 +2
6	15 VA	83	Bi	Bismuth	208.980	2 8 18 32 18 5	+3
6	16 VIA	84	Po	Polonium	[208.982]	2 8 18 32 18 6	+4 +2 -2
6	17 VIIA	85	At	Astatine	209.987	2 8 18 32 18 7	+1 -1
6	18 VIIIA	86	Rn	Radon	222.018	2 8 18 32 18 8	+2 0
7	1 IA	87	Fr	Francium	223.020	2 8 18 32 18 8 1	+1
7	2 IIA	88	Ra	Radium	226.025	2 8 18 32 18 8 2	+2
7	3 IIIB	89-103		Actinoids			
7	4 IVB	104	Rf	Rutherfordium	[261]	2 8 18 32 32 10 2	+4
7	5 VB	105	Db	Dubnium	[262]	2 8 18 32 32 11 2	+5
7	6 VIB	106	Sg	Seaborgium	[266]	2 8 18 32 32 12 2	+6
7	7 VIIB	107	Bh	Bohrium	[264]	2 8 18 32 32 13 2	+7
7	8 VIIIB	108	Hs	Hassium	[269]	2 8 18 32 32 14 2	+8
7	9 VIIIB	109	Mt	Meitnerium	[278]	2 8 18 32 32 15 2	
7	10 VIIIB	110	Ds	Darmstadtium	[281]	2 8 18 32 32 16 2	
7	11 IB	111	Rg	Roentgenium	[280]	2 8 18 32 32 17 2	
7	12 IIB	112	Cn	Copernicium	[285]	2 8 18 32 32 18 2	+2
7	13 IIIA	113	Nh	Nihonium	[286]	2 8 18 32 32 18 3	
7	14 IVA	114	Fl	Flerovium	[289]	2 8 18 32 32 18 4	
7	15 VA	115	Mc	Moscovium	[289]	2 8 18 32 32 18 5	
7	16 VIA	116	Lv	Livermorium	[293]	2 8 18 32 32 18 6	
7	17 VIIA	117	Ts	Tennessine	[294]	2 8 18 32 32 18 7	
7	18 VIIIA	118	Og	Oganesson	[294]	2 8 18 32 32 18 8	

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Lanthanoids

Atomic Number	Symbol	Name	Atomic Mass	Electron Shell Configuration	Oxidation States
57	La	Lanthanum	138.905	2 8 18 18 9 2	+3
58	Ce	Cerium	140.116	2 8 18 19 9 2	+4 +3
59	Pr	Praseodymium	140.908	2 8 18 21 8 2	+3
60	Nd	Neodymium	144.243	2 8 18 22 8 2	+3
61	Pm	Promethium	144.913	2 8 18 23 8 2	+3
62	Sm	Samarium	150.36	2 8 18 24 8 2	+3
63	Eu	Europium	151.964	2 8 18 25 8 2	+3 +2
64	Gd	Gadolinium	157.25	2 8 18 25 9 2	+3
65	Tb	Terbium	158.925	2 8 18 27 8 2	+3
66	Dy	Dysprosium	162.500	2 8 18 28 8 2	+3
67	Ho	Holmium	164.930	2 8 18 29 8 2	+3
68	Er	Erbium	167.259	2 8 18 30 8 2	+3
69	Tm	Thulium	168.934	2 8 18 31 8 2	+3
70	Yb	Ytterbium	173.055	2 8 18 32 8 2	+3
71	Lu	Lutetium	174.967	2 8 18 32 9 2	+3

Actinoids

Atomic Number	Symbol	Name	Atomic Mass	Electron Shell Configuration	Oxidation States
89	Ac	Actinium	227.028	2 8 18 32 18 9 2	+3
90	Th	Thorium	232.038	2 8 18 32 18 10 2	+4
91	Pa	Protactinium	231.036	2 8 18 32 20 9 2	+5
92	U	Uranium	238.029	2 8 18 32 21 9 2	+6
93	Np	Neptunium	237.048	2 8 18 32 22 9 2	+5
94	Pu	Plutonium	244.064	2 8 18 32 24 8 2	+4
95	Am	Americium	243.061	2 8 18 32 25 8 2	+3
96	Cm	Curium	247.070	2 8 18 32 25 9 2	+3
97	Bk	Berkelium	247.070	2 8 18 32 27 8 2	+3
98	Cf	Californium	251.080	2 8 18 32 28 8 2	+3
99	Es	Einsteinium	[254]	2 8 18 32 29 8 2	+3
100	Fm	Fermium	257.095	2 8 18 32 30 8 2	+3
101	Md	Mendelevium	258.1	2 8 18 32 31 8 2	+3
102	No	Nobelium	259.101	2 8 18 32 32 8 2	+2
103	Lr	Lawrencium	[262]	2 8 18 32 32 8 3	+3