



New Jersey Center for Teaching and Learning
Progressive Science Initiative

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Introduction to Atomic Structure

www.njctl.org

Chemistry

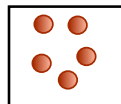
Chemistry is the study of matter and the changes it undergoes.

The type of matter that is changing and what types of changes it undergoes determines the field of chemistry that is being studied.

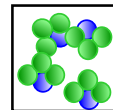


Matter

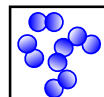
You will recall that we define matter as anything that has mass and takes up space.



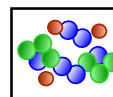
Atoms of an element



Molecules of a compound



Molecules of a diatomic element



Mixture of elements and a compound

Existence of the Atom

The idea of the atom has been around for some 2500 years in one form or another. In 1909 the existence of atoms was proved by Ernest Rutherford.

Let's go through a historical account of how scientists arrived at Rutherford's proven existence of the atom.

What is Matter Made of?

Ancient Greeks thought all matter was some combination of four "elements"



Earth



Air



Fire



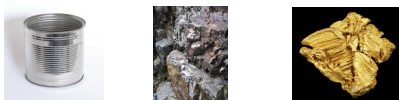
Water

So, according to this theory, what makes copper - or any other substance unique was its unique blend of these four elements.

Transmutations

According to this four element theory, if one were to just change the proportions of these four "elements", maybe you turn one substance into another - like tin into gold!

For instance, they may have thought that tin just needs a little more of the "element" earth in order to be turned into gold.



tin + earth ---> gold Yay!!

Except, it never worked for them. Transmutation does occur in the natural world but to do it artificially requires modern technology and not according to this theory!

An alternate ancient theory

A greek philosopher named Democritus believed that matter consisted of tiny spheres which he called "atomos" moving through empty space, which he called the "void".

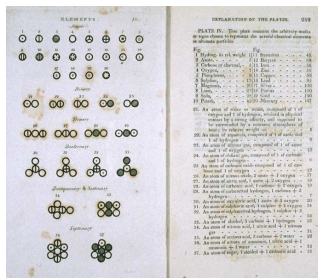


The word "atomos" means indivisible in Greek and this is where we get the word "atom" of course.

There were a number of holes in his theory, among them being that atoms are divisible, but he was on to something.

Dalton's Postulates

Building on Democritus' idea, in the early 1800s, English chemist John Dalton was the first scientist to observe the physical world and matter and via these observations, this draw some conclusions about atoms.



Various atoms and molecules as depicted in John Dalton's 1808 book: *A New System of Chemical Philosophy*

Dalton's Atomic Theory

Dalton had a few major components to his theory

Matter is composed of atoms, which are indivisible. Each compound consists of a set ratio of atoms.	
Atoms of same element are identical	
Atoms of different elements are different	
Atoms are not changed, created, or destroyed in a reaction, they are simply rearranged	

Law of Conservation of Mass

Dalton knew that chemical reactions occur by rearrangement of atoms. The law of conservation of mass had already been discovered. The masses of chemicals before and after a reaction remained the same, so the number of atoms before and after a reaction had to be the same as well!

[click here for an explanation of conservation of mass](#)



1 Which one of the following is not one of the postulates of Dalton's atomic theory?

- A Atoms are made of protons, neutrons, and electrons.
- B All atoms of a given element are identical
- C Atoms are neither created nor destroyed in chemical reactions.
- D Compounds are formed when atoms of more than one element combine
- E Each element is composed of extremely small particles called atoms.

Dalton's Postulates

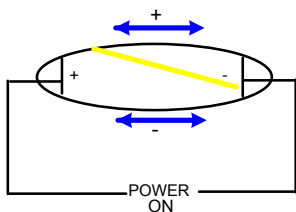
Dalton had the right idea with his postulates but he was not completely correct. He was limited by the equipment he had to observe reactions.

Today we know that there are some forms of reactions in which mass does change, and atoms are changed from one type to another. You learned about these last year in Physics. They are called Nuclear Reactions.

Also remember that today we know atoms can be broken down into smaller bits. We also know all atoms of an element are not identical - elements found in nature can vary in number of neutrons. However, for the purposes of general Chemistry, Dalton's Postulates are still a pretty reasonable approximation of what is actually happening in chemical reactions.

Digging into the Atom: Discovery of the Electron

Scientists found that they could deflect this beam by subjecting it to an additional electrical field.

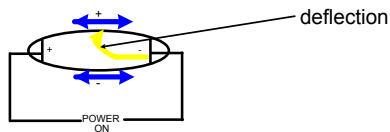


The deflection of the beam towards the positive electrode indicates that the beam carried a negative charge and traveled from the cathode to the anode. Since they "originated" from the cathode, they were called "*cathode rays*".

Digging into the Atom: Discovery of the Electron - DISCUSSION QUESTION

Once these rays were understood to be particles, they were in search of their properties - like their mass and the size of their charge.

Scientists determined that a very weak electrical field could deflect the beam a great deal. What does this tell us about the ratio of the charge to the mass of these particles?



Digging into the Atom: Discovery of the Electron

In the late 1800's scientists were passing electricity through glass tubes containing a very small amount of a particular gas such as oxygen.

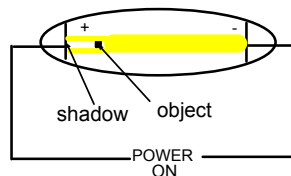


When the power was turned on, the tube emitted light, i.e. it glowed.

Note: The positive electrode was called the anode and the negative called the cathode.

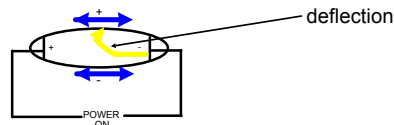
Digging into the Atom: Discovery of the Electron

There was much speculation about what these "cathode rays" were. Some thought they were a wave, others a stream of particles. To test this, they placed an object so as to interrupt the beam.



Since only particles would fail to pass through an object, they believed that these "cathode rays" were particles.

Digging into the Atom: Discovery of the Electron - DISCUSSION ANSWER



Since the particles were easily deflected, they must have either a really small mass (small things are easier to move than big things) or a really large charge (opposites attract). Therefore, the ratio should be a huge number

If the charge was really big:

$$\frac{\uparrow \text{charge}}{\text{mass}} = \text{large ratio}$$

If the mass was really big:

$$\frac{\text{charge}}{\downarrow \text{mass}} = \text{large ratio}$$

Digging into the Atom: Discovery of the Electron

A scientist named J.J. Thomson was able to determine this charge to mass ratio to be:

1.76×10^{11} Coulombs of charge/ kg of mass or C/kg

Keep in mind, at this point they knew neither the charge nor the mass, just that the ratio was large indicating EITHER a large charge or a small mass. What was VERY interesting was that these particles were found in all gases they experimented on and they all had the same charge to mass ratio.

2 What characteristic about the cathode rays led them to believe they were negatively charged?

- A They were small
- B They were easily deflected
- C They were deflected towards a positive electrode
- D They moved quickly
- E They were found in all atoms

4 Which one of the following is not true concerning cathode rays?

- A They originate from the negative electrode.
- B They travel in straight lines in the absence of electric or magnetic fields.
- C They move from the cathode to the anode.
- D They are made up of electrons.
- E The characteristics of cathode rays depend on the material from which they are emitted.

Thompson's Major Conclusion

These particles, now called "Electrons" must be a fundamental building block of all atoms.

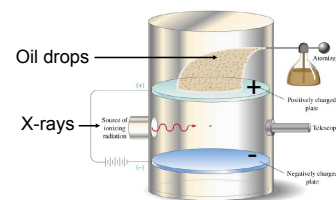
Atoms were indeed divisible!

3 What evidence indicated that these cathode rays had particle like properties?

- A They were small
- B They were not able to pass through a thick object
- C They moved very quickly
- D They were easily deflected towards a positive electrode
- E They were not altered by a magnetic field

Millikan Oil Drop Experiment: Finding the charge and mass of an electron

A scientist named Millikan squirted oil drops into a box and then passed high energy x-rays at the box hoping to knock electrons off the air molecules and onto the oil drops.



[Click here to see an animation of the experiment](#)

By measuring the energy necessary to stop the drops from descending, he was able to determine the charge per drop. The more energy needed to prevent the drop from falling, the smaller the charge of the drop.

Millikan Oil Drop Experiment: Sample Data

Finding the charge and mass of an electron
Here is some sample data from Millikan's experiment

Drop	Charge (Coulombs)
1	4.8 E -19
2	3.2 E -19
3	6.4 E -19
4	9.6 E -19

Interestingly, he found that the charges on each drop were a multiple of a number. Can you find what number they are all a multiple of?

move for answer

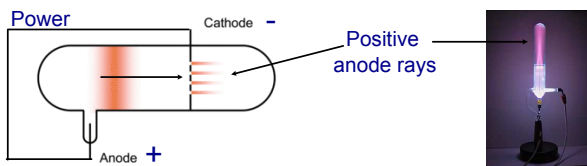
He correctly interpreted this to be the charge of an electron.

5 Which of these could be the charge of a drop in the millikan oil drop experiment?

- A $0.80 \times 10^{-19} \text{ C}$
- B $2.0 \times 10^{-19} \text{ C}$
- C $8.0 \times 10^{-19} \text{ C}$
- D $4.0 \times 10^{-19} \text{ C}$

Discovery of the Proton

After the discovery of the electron, scientists believed that there must also be a positively charged particle in the atom. To look for these, they used an anode ray tube.



By placing holes in the cathode so particles could move through it, they found that particles were indeed moving from the anode to the cathode. Since they move towards a negative plate, they must be positive.

Finding the charge and mass of an electron

Once the charge was known, it was easy to use Thomson's charge to mass ratio to find the mass.

$$1.6 \times 10^{-19} \text{ C} \times \frac{1 \text{ kg}}{1.76 \times 10^{11} \text{ C}} = 9.09 \times 10^{31} \text{ kg}$$

This is one tiny mass!
Electrons are super super small.

6 The magnitude of the charge on an electron was determined in the _____.

- A cathode ray tube, by J. J. Thomson
- B Millikan oil drop experiment
- C Dalton atomic theory
- D atomic theory of matter

Discovery of the Proton

The anode rays were referred to as protons, which were found to be significantly heavier than electrons.

1 proton = 1840 x mass of electron

Since the heaviest anode rays in oxygen were found to be 8 x heavier than those in hydrogen, it was assumed that oxygen had 8 protons compared to hydrogen's 1.

The number of protons an atom has is its atomic number (Z) and it is different for each element on the periodic table.

Discovery of the Proton

Unlike the cathode ray/electron, each anode ray had different masses depending on the gas used in the tube. More interesting was the fact that each element seemed to have some anode rays with the mass of those found in hydrogen.

They concluded that the anode rays found in hydrogen were a fundamental particle like the electron and found in all atoms.

8 Which of the following is NOT true regarding protons and electrons?

- A Both were found in all atoms
- B Both have the same charge
- C Protons are significantly heavier than electrons
- D Not all elements have the same number of protons
- E All of these are true

9 Barium is used to help take X-rays of the digestive system of the human body. What is the atomic number of barium (Ba)?

- A 38
- B 48
- C 137
- D 4
- E 56



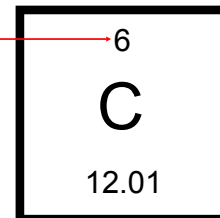
7 Which of the following is TRUE regarding protons?

- A They were originally called cathode rays
- B They move faster than cathode rays
- C They have a larger mass than electrons
- D They moved from the cathode to the anode
- E They have the same charge as an electron

Atomic Number and Protons

Each element symbol on the periodic table clearly labels the atomic number.

Atomic Number (Z)



Note: Periodic Tables vary in their location of the atomic number. It is always a whole number.

10 Which is the correct number of protons in an atom of vanadium (V)?

- A 23
- B 51
- C 18
- D 24
- E 50

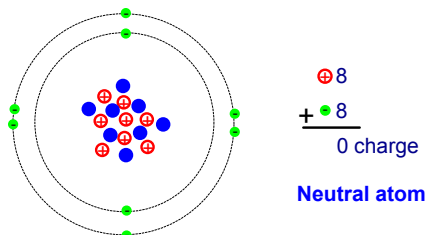


Atomic Number, Protons, Electrons, and Ions

If an atom is electrically neutral, it will have the same number of protons and electrons.

Neutral Oxygen ----> 8 (+) protons and 8 (-) electrons

Neutral Magnesium ----> 12 (+) protons and 12 (-) electrons

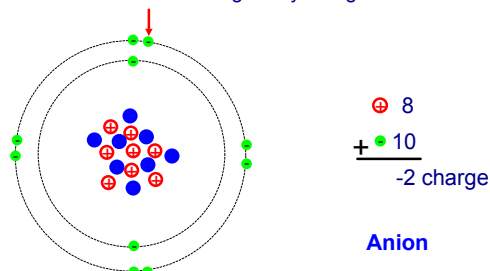


Atomic Number, Protons, Electrons, and Ions

If an atom loses or gains electrons, it will become charged and is known as an ion.

Cation = positively charged ion

Anion = negatively charged ion



Ions

When an atom loses electrons, it loses negative charge, and will become a positive cation.

Mg	Mg ²⁺
12 protons	12 protons
12 electrons	10 electrons

When an atom gains electrons, it gains negative charge, and will become a negative anion

O	O ²⁻
8 protons	8 protons
8 electrons	10 electrons

Note: The charge on an ion is typically listed as a superscript to the upper right of the symbol

Working with Ions

Fill in the table below to practice working with ions

Symbol	protons	electrons	charge
P ³⁻	15		
		18	+2
Fe ³⁺			

11 Fluoride ions are used in toothpaste. How many protons and electrons are present in a F⁻ ion?

- A 9 protons, 9 electrons
- B 9 protons, 10 electrons
- C 9 protons, 8 electrons
- D 19 protons, 20 electrons
- E 19 protons, 18 electrons



12 What would be the correct number of electrons present in a nitride ion (N³⁻)?

- A 7
- B 4
- C 17
- D 10
- E 14

3 Major ideas we know now

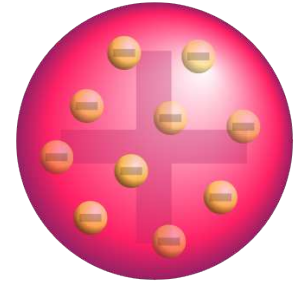
- (1) Matter is composed of atoms
- (2) Atoms are composed of two charged subatomic particles: protons and electrons.
- (3) Different elements have different numbers of protons and electrons.

The question scientists were grappling with was how these particles are arranged inside the atom, in other words, how can the structure of an atom be determined?

Plum pudding model

The prevailing theory about the make-up of an atom was the "plum pudding" model - proposed by J. J. Thomson around 1900.

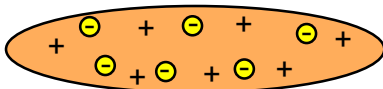
The model featured a positive sphere of matter with negative electrons embedded in it.



Plum Pudding Model

The original proposal for the atom was based around the idea that positive and negative charges attract and like charges repel.

Scientists pictured the electrons spread out in the midst of protons.



The negatively charged electrons served as "plums" spread throughout the "pudding" - the protons.

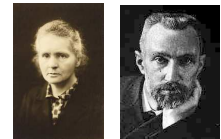
Of course, models must be tested and the search was on to find evidence to support the "plum pudding" model.

Radioactivity

Radioactivity is the spontaneous emission of radiation by an atom.

It was first observed by Henri Becquerel.

Marie and Pierre Curie also studied it.

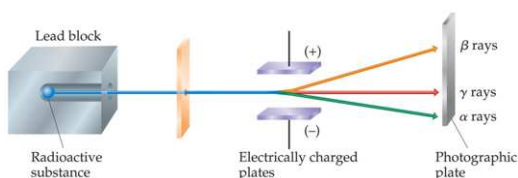


The 3 shared the 1903 Nobel prize in physics for their work. Marie Curie also went on to win the 1911 Nobel Prize for Chemistry.

Radioactivity

Three types of radiation were discovered by Ernest Rutherford:

- alpha particles (positively charged particles with a mass roughly 4x that of the proton)
- beta particles (electrons)
- gamma rays (form of light with very high energy)



13 Of the three types of radioactivity characterized by Rutherford, which are particles?

- A β -rays
 B α -rays, β -rays, and γ -rays
 C γ -rays
 D α -rays and γ -rays
 E α -rays and β -rays

14 Beta-particles are attracted to a _____ charged plate, indicating they are _____ charged.

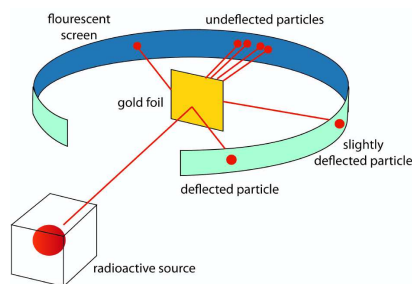
- A positively, negatively
- B negatively, positively
- C neutrally, negatively
- D neutrally, positively
- E neutrally, neutrally

15 Alpha particles are _____ charged.

- A negatively
- B positively
- C neutrally
- D Unknown

Rutherford's Gold Foil Experiment

Physicists Geiger and Marsden under the direction of Ernest Rutherford shot a beam of alpha particles at a thin sheet of gold foil and observed the scatter pattern of the particles.

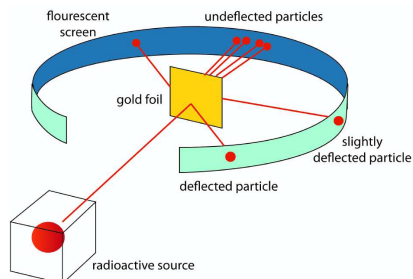


[Click here to see an animation of the experiment](#)

Discovery of the Nucleus

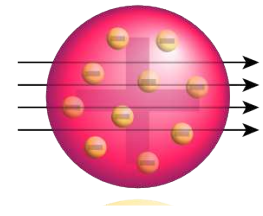
What actually happened was very surprising.

Most of the particles flew right through the foil with no deflection at all.



Discovery of the Nucleus

In the Plum Pudding Model of the atom, positive and negative charges are dispersed evenly throughout the atom. If this model were correct, the high energy alpha particles would be slightly deflected by weak electric fields as they passed through the foil.



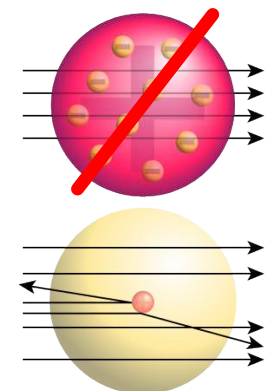
Rutherford and team expected all alpha particles to pass through the atoms in the gold foil and be deflected by only a few degrees.

Discovery of the Nucleus

While most particles went straight through

some bounced back...

totally unexpected!

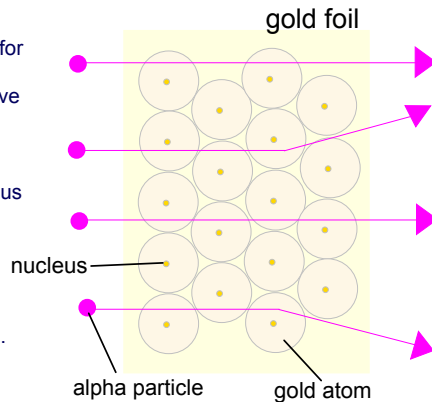


Rutherford's Gold Foil Experiment

The only way to account for the large angles was to assume that all the positive charge was contained within a tiny volume.

A small very dense nucleus must lie within a mostly empty atom.

Now we know that the radius of the nucleus is 1/10,000 that of the atom.



In Rutherford's words...

Then I remember two or three days later Geiger coming to me in great excitement and saying "We have been able to get some of the alpha-particles coming backward ..."

It was quite the most incredible event that ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.

- Rutherford

17 In the Rutherford nuclear-atom model:

- A the heavy subatomic particles reside in the nucleus
- B the principal subatomic particles all have essentially the same mass
- C the light subatomic particles reside in the nucleus
- D mass is spread essentially uniformly throughout the atom

The Nuclear Atom

Since most particles passed through and some particles were deflected at large angles, Thomson's model could not be correct.

The way in which the positive particles bounced off the thin foil indicated that the majority of the mass of an atom was concentrated in one small region.

Because the majority of the positive particles continued on their original path unmoved, Rutherford was forced to conclude that most of the remainder of the atom was a region of very low density.

#16 The gold foil experiment performed in Rutherford's lab _____.

- A confirmed the plum-pudding model of the atom
- B led to the discovery of the atomic nucleus
- C was the basis for Thomson's model of the atom
- D utilized the deflection of beta particles by gold foil
- E proved the law of multiple proportions

Discovery of the Neutron

Since electrons were so much smaller than protons, Rutherford believed the mass of an atom would be simply related to the number of protons present. However, they found that atoms were heavier than predicted!!

Example - Helium (He)

Helium = 2 protons, 2 electrons

Expected mass = 2 x (mass of proton)

Actual mass = 4 x (mass of proton)

Discovery of the Neutron

Example - Helium (He)

Helium = 2 protons, 2 electrons

Expected mass = 2 x (mass of proton)

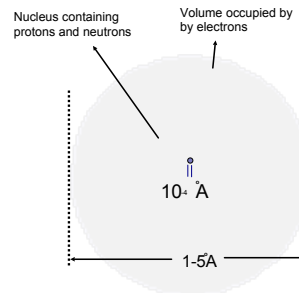
Actual mass = 4 x (mass of proton)

Helium was twice as heavy as expected. There must be another particle! This other particle was the neutron and its existence was suggested by Rutherford two years after his experiment and determined experimentally in 1932.

The Nuclear Atom

Rutherford postulated a very small, dense nucleus with the electrons around the outside of the atom.

Most of the volume of the atom is empty space.



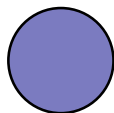
scale: 10^{-10} m = 1 nm

10^{-10} m = 10^{-9} m

[Click here to see Atom animation](#)

Neutrons, Protons, and Electrons

Neutrons have a mass that is essentially the same as a proton and no charge. The mass of a proton or neutron is described as an atomic mass unit or amu.



proton
+
1 amu



neutron
no charge
1 amu



electron
-
1/1840 amu

18

Neutrons, Protons, and Atomic Masses

Since electrons have a much smaller mass than a proton or neutron, the mass of an atom (in amu) is generally considered to be equal to the sum of the protons and neutrons in an atom.

(# of protons) + (# of neutrons) = atomic mass (A) in amu

19

20

21

22

Atomic Symbols and Atomic Masses

There are two common ways to indicate the mass of a particular atom.

Method 1

The mass is written as a number after the symbol.

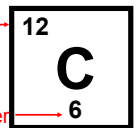
Method 2 (Nuclear Symbol)

The mass is written as a superscript to the left of the symbol.

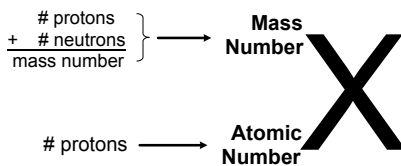
Ne-20

atomic mass (amu) →

atomic number →



Nuclear Symbols



Remember, when the atom is neutral, the number of protons equals electrons

23 How many neutrons are present in a neutral atom of Sr-80?

- A 38
- B 32
- C 38
- D 80
- E 42

24 Find the mass number.



Sodium Atom

25 How many protons does this element have?



Sodium Atom

26 How many electrons does this element have?



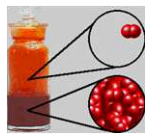
Sodium Atom

27 How many neutrons does this element have?



Sodium Atom

28 How many neutrons does this element have?



Bromine Atom

29 Which of the following has 45 neutrons?

- A ${}^{80}\text{Kr}$
- B ${}^{80}\text{Br}$
- C ${}^{78}\text{Se}$
- D ${}^{103}\text{Rh}$

###

30 An ion has 8 protons, 9 neutrons, and 10 electrons. The symbol for the ion is _____.

- A $^{17}\text{O}^{2-}$
- B $^{17}\text{O}^{2+}$
- C $^{19}\text{F}^{+}$
- D $^{19}\text{F}^{-}$
- E $^{17}\text{Ne}^{2+}$

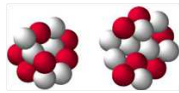
PRACTICE! Fill in the table below

Nuclear Symbol	Alternate Symbol	Atomic Number (Z)	Atomic Mass (A)	# of protons	# of neutrons	# of electrons	charge
$^{15}_7\text{N}$	N-15						0
			24			10	+1
		17			18	18	
	I-131						-1
$^{238}_{92}\text{U}$							0

Isotopes

Atoms of the same element can have different numbers of neutrons. For example, some Carbon atoms have 6 neutrons, some carbon atoms have 8 neutrons.

Atoms of the same element that have differing numbers of neutrons are called isotopes.



C-12 **C-14**

6 protons 6
6 neutrons 8
6 electrons 6

Note: Isotopes of an element will always have the same number of protons but differing masses due to the differing numbers of neutrons.

Isotopes

Write the complete symbol for each of these isotopes.



Neon 20
10 protons
10 neutrons
10 electrons



Neon 21
10 protons
11 neutrons
10 electrons



Neon 22
10 protons
12 neutrons
10 electrons



###

31 Which pair of atoms constitutes a pair of isotopes of the same element?

- A $^{14}_6\text{X}$ $^{14}_6\text{X}$
- B $^{14}_6\text{X}$ $^{14}_7\text{X}$
- C $^{14}_6\text{X}$ $^{14}_7\text{X}$
- D $^{14}_6\text{X}$ $^{14}_7\text{X}$
- E $^{14}_6\text{X}$ $^{14}_7\text{X}$

32 Which of the following is TRUE of isotopes of an element?

- A They have the same number of protons
- B They have the same number of neutrons
- C They have the same mass
- D They have the same atomic number
- E A and D

33 An atom that is an isotope of potassium (K) must...

- A Have 20 protons
- B Have 19 neutrons
- C Have 19 protons
- D A mass of 39
- E A total of 39 protons and neutrons

Isotopes and Atomic Masses

Not all isotopes are found in the same abundances in nature.



Neon 20
10 protons
10 neutrons
10 electrons

90.48%

So in a 10,000 atom sample of neon, you would on average find...

9048



Neon 21
10 protons
11 neutrons
10 electrons

0.27%

27

(atoms of each isotope of neon)



Neon 22
10 protons
12 neutrons
10 electrons

9.25%

925

Calculating Atomic Masses

To determine the atomic mass of an element, one must know the masses of the isotopes and how commonly they are found in nature. Then a weighted average is calculated as shown below.

Example: As we have seen, a sample of neon will consist of three stable isotopes - **Ne-20**, **Ne-21**, and **Ne-22**. If the relative abundance of these are 90.48%, 0.27%, and 9.25% respectively, what is the atomic mass of neon?

How to calculate average atomic mass:

1. Multiply each **isotope** by its **% abundance expressed as a decimal**
2. Add the products together

$$20(.9048) + 21(0.0027) + 22(0.0925) = 20.18 \text{ amu}$$

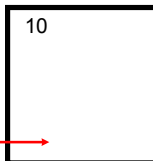
34 Which species is an isotope of ^{39}Cl ?

- A $^{40}\text{Ar}^+$
- B $^{34}\text{S}^{2-}$
- C $^{36}\text{Cl}^-$
- D ^{80}Br
- E ^{39}Ar

Atomic Masses and Mass Number

The atomic mass indicates the average atomic mass of all the isotopes of a given element. This is the number reported on the periodic table.

The mass number indicates the exact relative mass of a particular isotope of that element. These numbers are NOT reported on the periodic table.



Atomic mass \longrightarrow
(an average - no single neon atom has this mass)

Example: Calculate Atomic Mass

Carbon consists of two isotopes that are stable (C-12 and C-13). Assuming that 98.89% of all carbon in a sample are C-12 atoms, what is the atomic mass of carbon?



move for answer

###

35 Calculate the atomic mass of oxygen if it's abundance in nature is:

99.76% oxygen-16,
0.04% oxygen-17, and
0.20% oxygen-18.



(liquid oxygen)

36 Calculate the atomic mass of copper. Copper has 2 isotopes. 69.1% has a mass of 62.9 amu the rest has a mass of 64.93 amu.



37 Sulfur has two stable isotopes: S-32 and S-36. Using the average atomic mass on the periodic table, which of the following best approximates the natural relative abundances of these isotopes of sulfur?

- A 50% S-32 and 50% S-34
- B 25% S-32 and 75% S-34
- C 75% S-32 and 25% S-34
- D 95% S-32 and 5% S-34
- E 5% S-32 and 95% S-34

Application of Isotopes

Elephants are hunted for the ivory in their tusks. Game wardens use isotopes to track where elephants are going so they can help protect them.



If an elephant eats plants from a wet climate, the ratio of N-15 to N-14 in the hair will be lower than is typically found in nature.
If they graze plants grown in a dry climate, they will a higher ratio of N-15 to N-14 than normal in their hair.

Where would you look for an elephant that had a hair sample with a ratio of 0.0045 N-15/N-14 where the normal ratio is 0.0034 N-15/N-14?

Discovery of the Atom Timeline

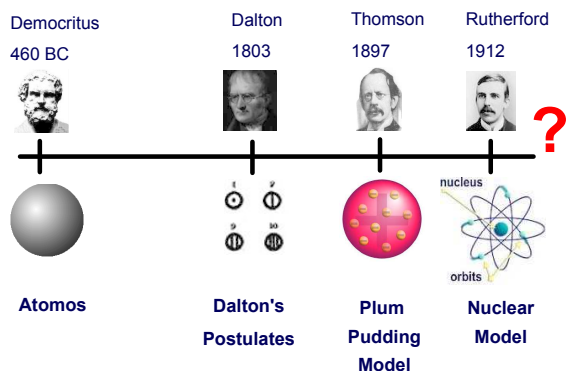
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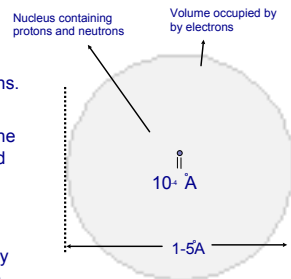
Evolution of Atomic Theory



The Problem with the Nuclear Atom

Where we are:

1. Atoms are composed of protons, neutrons, and electrons.
2. The protons and neutrons comprise the vast majority of the mass of an atom and are found together in the small, dense nucleus.
3. The electrons are found outside the nucleus and occupy the vast majority of the volume.



Question: Can anyone think what might be a problem with this model?

Problem with the nuclear atom

A new approach is needed

Classical physics failed to explain how atoms could exist.
A new approach was needed.

The next step led to the Bohr model of the atom, which was a semi-classical explanation of atoms. It would be an important transition to modern quantum theory.

An important clue would be found in the kind of light we see produced when atoms are energized.

The Problem with the Nuclear Atom

Perhaps electrons orbit the nucleus...like planets orbit the sun. But then they would constantly be accelerating as they travel in a circle:

$$a = v^2/r$$

But it was known that an accelerating charge radiates electromagnetic energy...light.

As a charge radiates light it loses energy. All the kinetic energy would be radiated away in about a billionth of a second...then the electron would fall into the nucleus. All the atoms in the universe would collapse.

