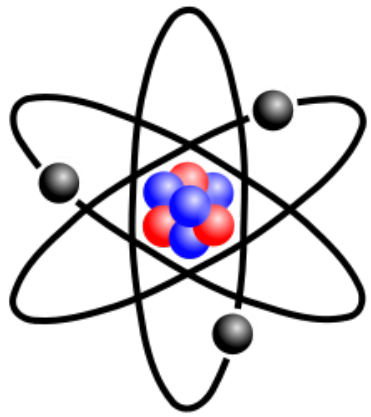
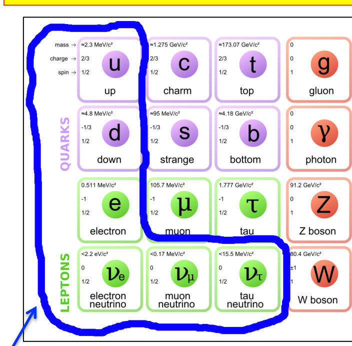
Matter: What it is



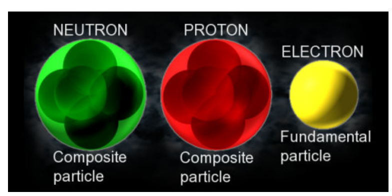
What does it Matter?

1. Our world is made of energy and matter.
2. Matter is a conglomeration of fundamental particles.
3. Some particles are composites of fundamental particles.
4. The fundamental unit of matter is the atom.



The common fundamental particles of everyday life are quarks, electrons, and neutrinos.

These particles will play a large role in our understanding of stars and galaxies. For every particle there is an "anti-particle".



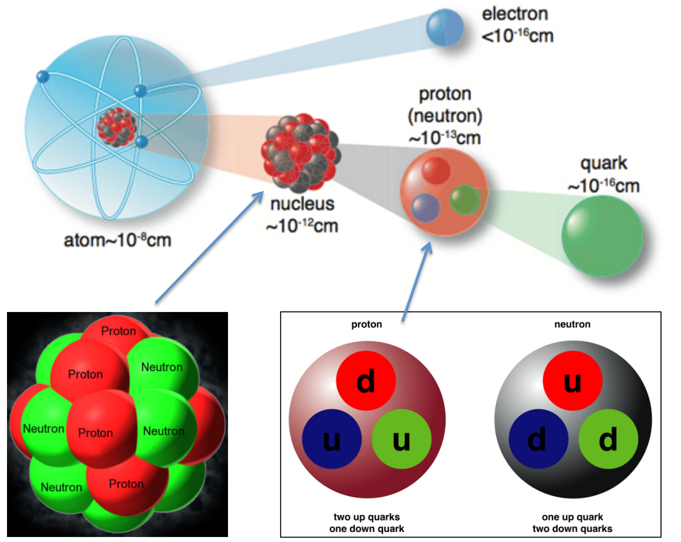
A **fundamental particle** cannot be broken down into other particles. An electron is a fundamental particle.

A **composite particle** is built from fundamental many fundamental particles. Protons and neutrons are composite particles.

Atoms are complex entities made of protons, neutrons, and electrons.

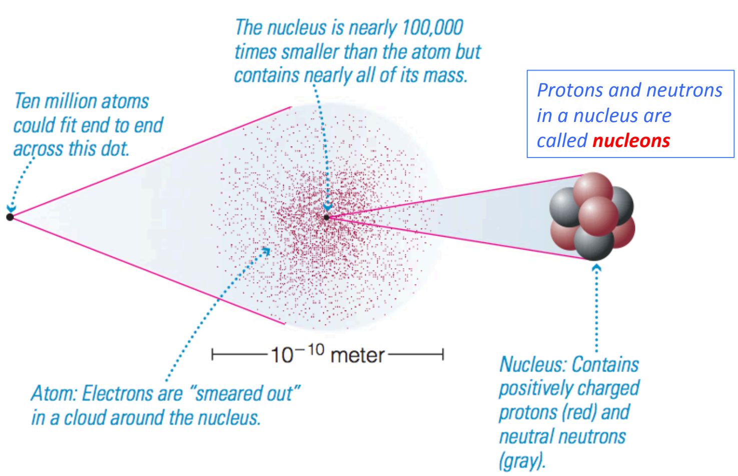
Protons and neutrons are made of "u" and "d" quarks.

Atoms: the fundamental unit of matter



The Atom

Protons → positive electric charge
Neutrons → no electric charge (neutral)
Electrons → negative electric charge

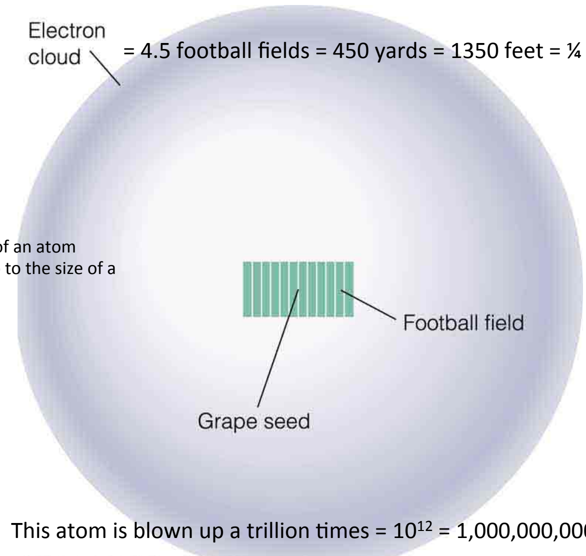


The negatively charged electrons orbit the positively charged nucleus.
The charge of an electron equals the charge of a proton (just opposite signs).

The nucleus is extremely tiny compared to the orbits of the electrons
Atoms are truly empty space!

= 4.5 football fields = 450 yards = 1350 feet = ¼ mile

If the nucleus of an atom were scaled up to the size of a grape seed…

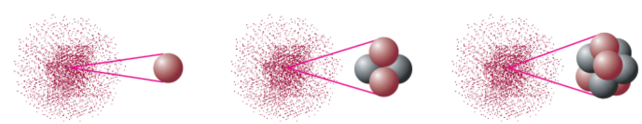


This atom is blown up a trillion times = 10^{12} = 1,000,000,000,000

Atomic Number and Element Identity

atomic number *= number of protons*
atomic mass number *= number of protons + neutrons*
(A neutral atom has the same number of electrons as protons.)

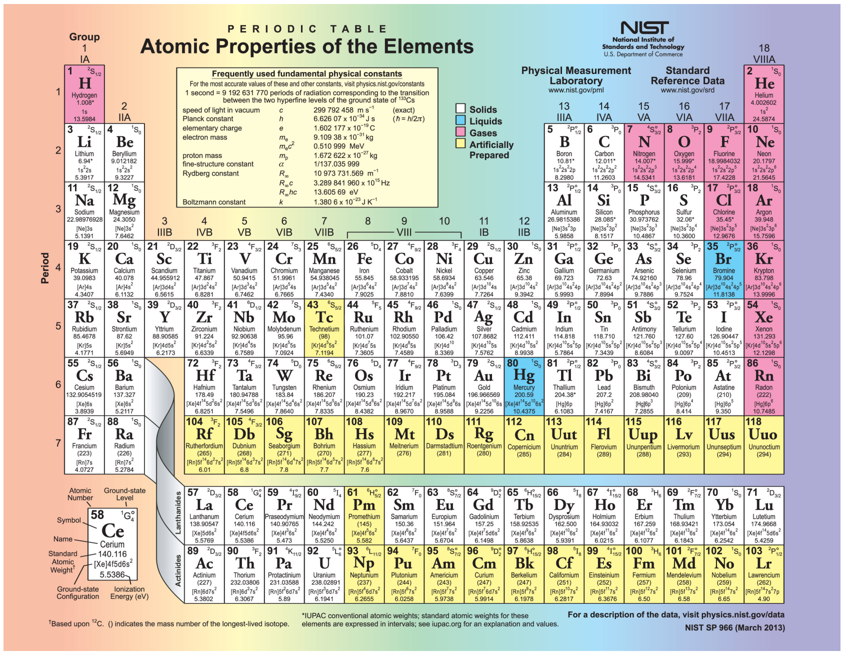
Hydrogen (^{1}H)	Helium (^{4}He)	Carbon (^{12}C)



atomic number = 1	atomic number = 2	atomic number = 6
atomic mass number = 1	atomic mass number = 4	atomic mass number = 12
(1 electron)	(2 electrons)	(6 electrons)

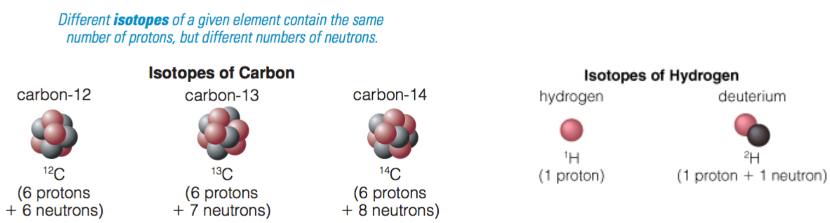
An element is defined by the number of protons in its nucleus. This dictates the charge of the nucleus and thus the number of electrons that orbit the nucleus (when the atom actually has all of its electrons- more on that later).

Example: carbon → 6 protons, so atomic number = 6, and thus 6 orbiting electrons.
The number of electrons dictate how the atom bonds with other atoms and how light will interact with the atom.



Isotopes

Not all carbon (6 protons) has 6 neutrons; some has 7 neutrons, and some has 8 neutrons. With 6 protons, the carbon atoms with different numbers of neutrons are still carbon atoms! (and they still have 6 electrons orbiting them).



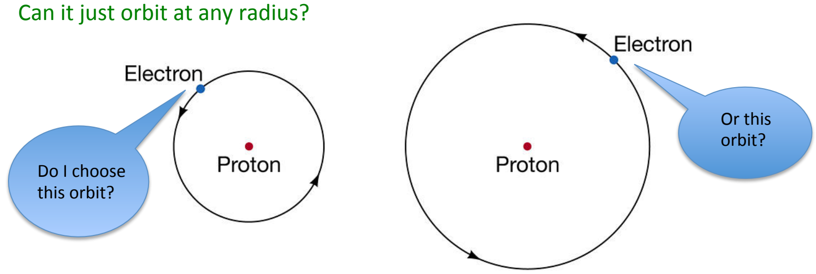
A given element does not always have the same number of neutrons (or mass). These different "versions" the same element are called isotopes.

These isotopes, especially deuterium, are very important in the way stars generate energy to survive their own crush against gravity.

The Electron Orbits

The electrons bound to atoms are very important, because they are the parts of the atoms that interact with light, and light provides the direct information to us from across the universe. Understanding how electrons are bound to atoms allows us to decode the light.

How does the electron decide the radius, and thus energy, of its orbit?
Can it just orbit at any radius?

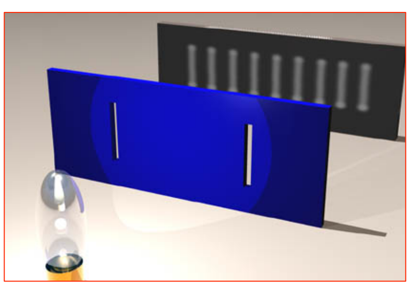


The answer is NO. But why?

Only certain orbits are allowed because an electron behaves as if it is both a particle and a wave.

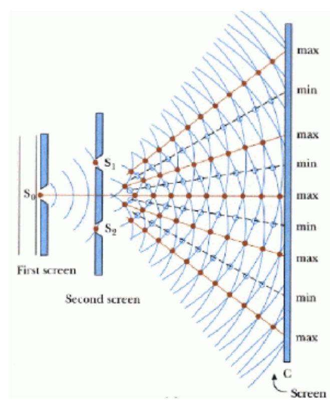
Wave particle duality of electrons!

It's a particle. No, it's a wave…. No! It's a particle… no, …



When you send light through a double slit, the electromagnetic waves passing from each slit interfere and yield multiple images of the slits.

Particles, on the other hand, would either pass through one slit or the other and would yield an imaged of two slits only.



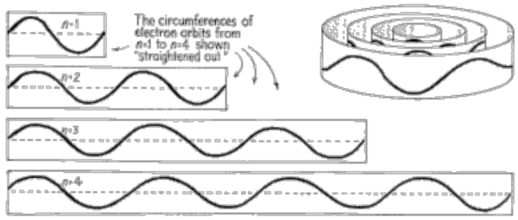
A beam of electrons aimed at a double slit yields the same multi-slit pattern as light waves.

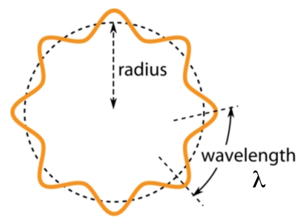
Electrons acts as if they are waves!

The Key to Electron Orbits

http://youtu.be/no7ZPPqtZEg VIDEO: standing waves (0.53)

Since a wave can interact with itself, it can persist only if the self-interaction is self sustaining. This means the circumference of the electron orbit has to equal an integer number of wavelengths. The electron becomes a standing wave and is locked into a fixed orbital radius.



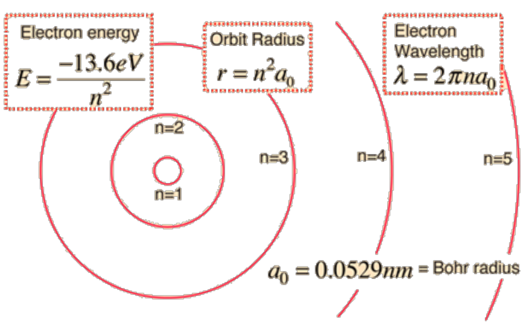


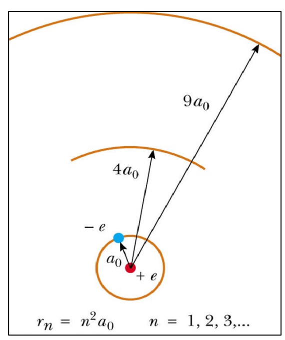
circumference of orbit = $2\pi r$ must equal $n\lambda$ where "n" is an integer (1,2,3,etc).

Nothing restricts what "n" can be, so an electron orbiting a nucleus can choose from many possible "allowed" orbits, but only occupies one orbit at any given time.

The Hydrogen Atom

… showing some of the smallest allowed orbits



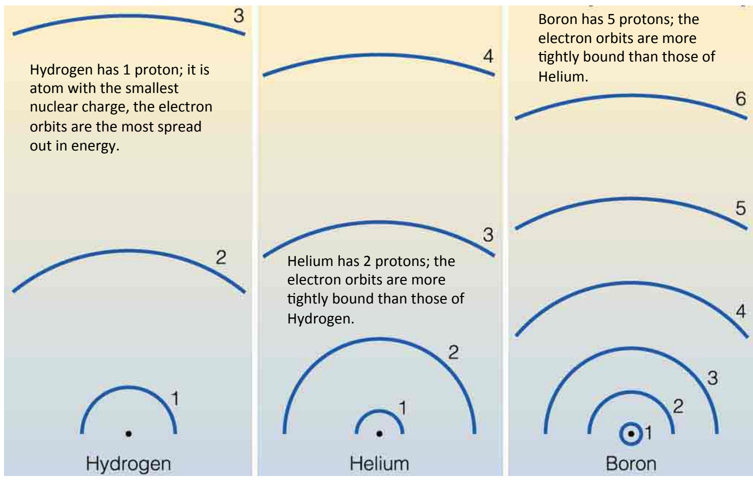


Note that each orbit has an associated energy that depends upon "n". Thus, the energy of the atom depends upon which allowed orbit the electron is in.

a_0 is called the Bohr radius = 0.053 nm. It is the n=1 radius of the electron. It is computed from fundamental constants of nature, such as: π, c=speed of light, e=electron charge, m=mass of electron. a_0 is 0.013% of the wavelength of blue light

Different Elements have Different Allowed Orbits

The greater the number of protons in the nucleus, the more tightly bound the electrons.
The orbital energies and radii scale with the square of the charge of the nucleus.
Thus, each element has its own unique set of allowed orbits and energies.



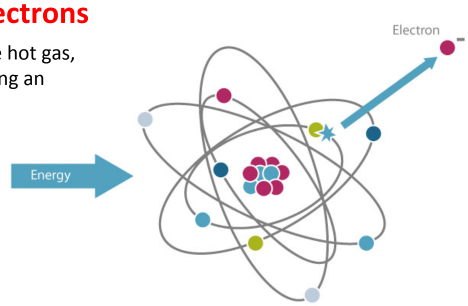
Ions: Atoms with missing electrons

In energetic environments, such as a dense hot gas, some energy can be channeled into knocking an electron off an atom.

- This process is called ionization.
- The atom now has a net positive charge.
- The liberated electron is free in the gas.

Some ions can have several of their electrons removed

An atom is fully ionized when all of its electrons have been removed; the ion is now a bare nucleus (and all its electrons a freely zooming around in the gas).



Photoionization: The energy comes from a high-energy photon (UV, X-ray). The photon electro-magnetic energy is converted into energy to first free the electron with the remaining energy converted into the kinetic energy* of the now freed electron

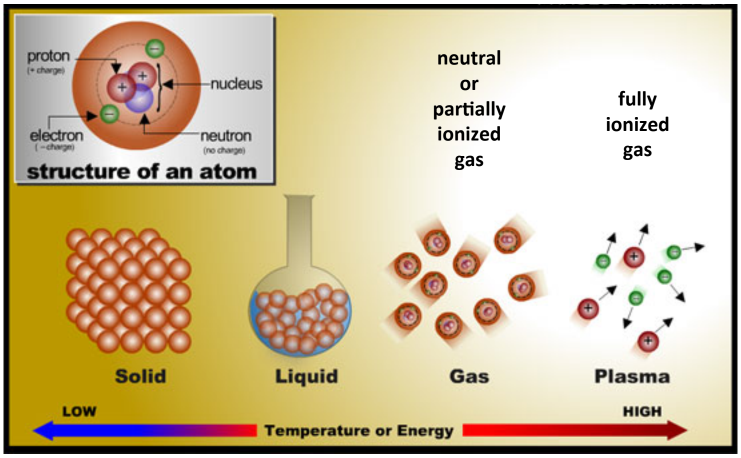
Collisional ionization: The energy comes from a fast moving particle in the gas. Some of its kinetic energy is converted passed to the bound electron, setting it free into the gas

Three categories of gases

- Neutral
  - all electrons bound to atoms
- Partially Ionized
  - some electrons bound to atoms, others free in the gas
  - atoms in various stages of ionization
- Fully Ionized → called Plasma
  - all electrons stripped from all atoms
  - all atoms in the gas are just the bare nucleus
  - all the electrons in the gas are freely moving

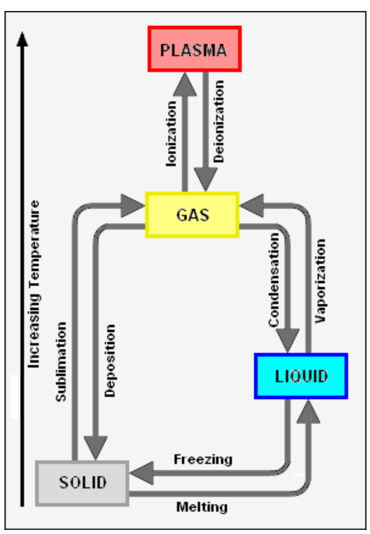
- kinetic energy = energy of motion, depends on object mass and velocity squared: $KE=(m/2)*v^2$

Four States of Matter:



Most of the matter in the universe is contained in partially ionized gas and plasmas. Stars are plasmas throughout, until you get to the very outer cooler layers, where the gas is partially ionized.

Matter in the Universe



Solids:
planets, moon, comets, asteroids, ices

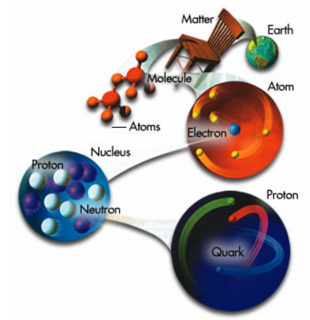
Liquids:
oceans on/in planets or moons
superfluids in neutron stars

Gas → Plasma:
planet atmospheres
stars
interstellar medium
circumgalactic medium
intracluster medium
intergalactic medium
regions around massive black holes

Diagram shows the interrelationship between various states of matter; most of the matter in the universe is in the form of a gas with some level of ionization in it.

How Matter Interacts with Matter

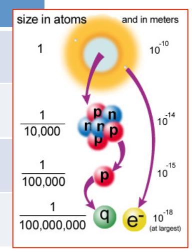
What holds atoms together?
How do elements turn into other elements?



The are Four Fundamental Forces in the Universe

From strongest to weakest they are:
1. Strong Nuclear Force
2. Electromagnetic Force
3. Weak (Nuclear) Force
4. Gravitational Force

Force	Theory Name	Force Carriers	Relative Strength	Distance Behavior	Range (m)
Strong	Quantum Chromodynamics	gluons	10^{38}:1	none	10^{-15} (size of proton)
Electromagnetic	Quantum electrodynamics	photons	10^{36}:1	$1/r^2$	infinity
Weak	Electroweak	W and Z particles	10^{25}:1	$(1/r)\, e^{-mr}$	10^{-18} (size of quark)
Gravitation	General Relativity	(gravitons)	1:1	$1/r^2$	infinity

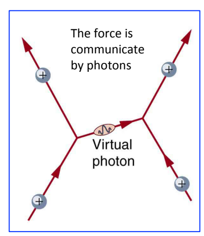


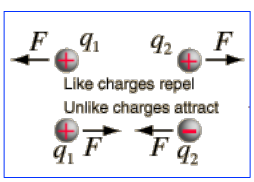
2. Electromagnetic Force

Though it is 2nd strongest force, we discuss it first.

Particles with electric charge interact via an electrical force, *F*, that they both feel equally

- **Like charges repel each other**
- **Opposite charges attract each other**

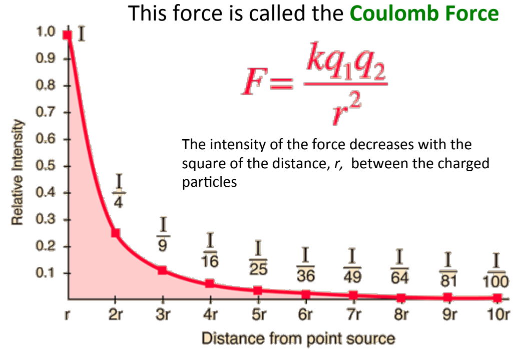




This force is called the **Coulomb Force**

$$F = \frac{kq_1q_2}{r^2}$$

The intensity of the force decreases with the square of the distance, *r*, between the charged particles



The Coulomb Force (electromagnetic) is the force that binds negatively charged electrons in their orbits around the positively charge atomic nucleus in atoms.

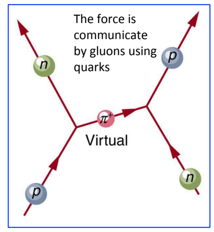
http://en.wikipedia.org/wiki/Strong_interaction#mediaviewer/File:Nuclear_Force_anim_smaller.gif (animation)

1. Strong Nuclear Force

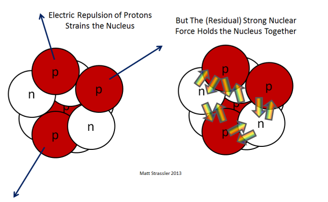
Crazy glue for the nucleus

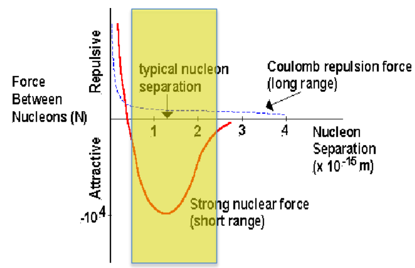
Protons and neutrons in close proximity feel a "color" force

- **Quarks are exchanged between nucleons**
- **Protons and neutrons exchange identities**



Without the strong force, the Coulomb force would blow the nucleus apart because the protons electrically repel each other (quite strongly!)





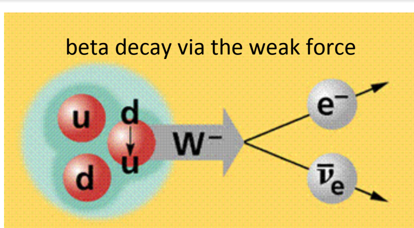
The strong force is the force that binds protons and neutrons together in the nucleus of atoms.

The attractive power of the strong force is much stronger than the repulsive power of the Coulomb force at the separation distances typical of protons and neutrons in a nucleus.

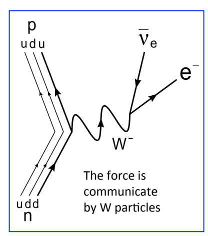
3. Weak Nuclear Force

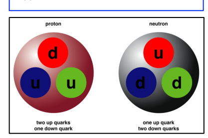
Radioactivity and Transmutation

Force by which protons transform into neutrons and neutrons transform into protons- releases radiation in the process.



A "down" quark in a neutron ejects a negatively charged W particle and turns into an "up" quark. The neutron is now a positively charged proton. The W particle decays into an electron and an anti-neutrino. The ejected electron shoots out of the atom- this is a form of radiation called **beta decay**. Note that the element changes identity (called **transmutation**) because there is now 1 more proton in it's nucleus.



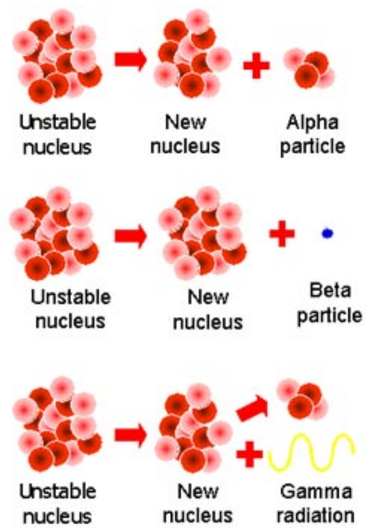


Neutron = udd
Proton = uud

The weak force is the force responsible for radioactivity, in which particles like electrons are ejected from the nucleus of atoms. It is also the force by which elements can change identities!!!

3 Forms of Radiation

Alpha, Beta, Gamma



Alpha (α): atom decays into a new atom & emits an alpha particle (2 protons and 2 neutrons: the nucleus of a helium atom)

"New" nucleus has two less protons so is a different element with lower atomic number

Beta (β): atom decays into a new atom by changing a neutron into a proton & electron. The fast moving, high energy electron is called a beta particle

"New" nucleus gains a proton so is a different element with higher atomic number

Gamma (γ): after α or β decay, surplus energy is sometimes emitted. This is called gamma radiation & has a very high frequency with short wavelength. The atom is not changed

New nucleus element has same number of protons after gamma radiation is emitted

We will talk about the Gravitational Force in a later lecture.

The strong, weak, and electromagnetic forces all work together and are responsible for why matter is structured into atoms and why atoms interact with each other as we observe.

The weak force being responsible for radioactivity (i.e, why there is radiation) in the universe.

These forces are why stars shine.

They are why the elements exist.

The entire evolution of the universe is a result of how these forces work.