Saturday Morning Physics -- Texas A&M University

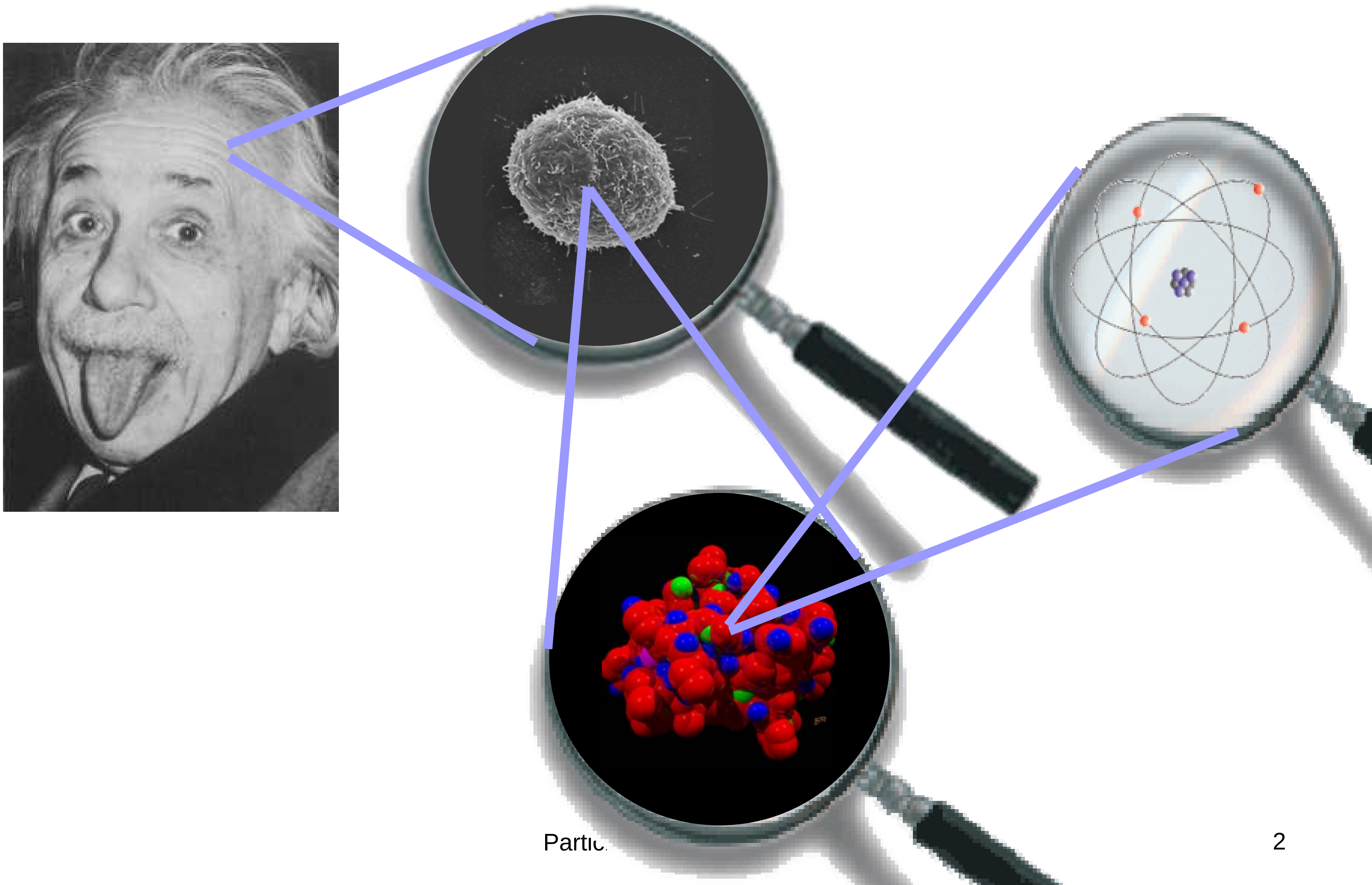
Particles and Forces

What is Matter and what holds it together?

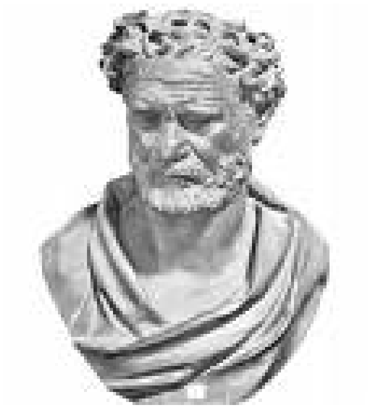
Dr. Rainer J. Fries

January 27, 2007

Zooming in on the World around us



Atoms



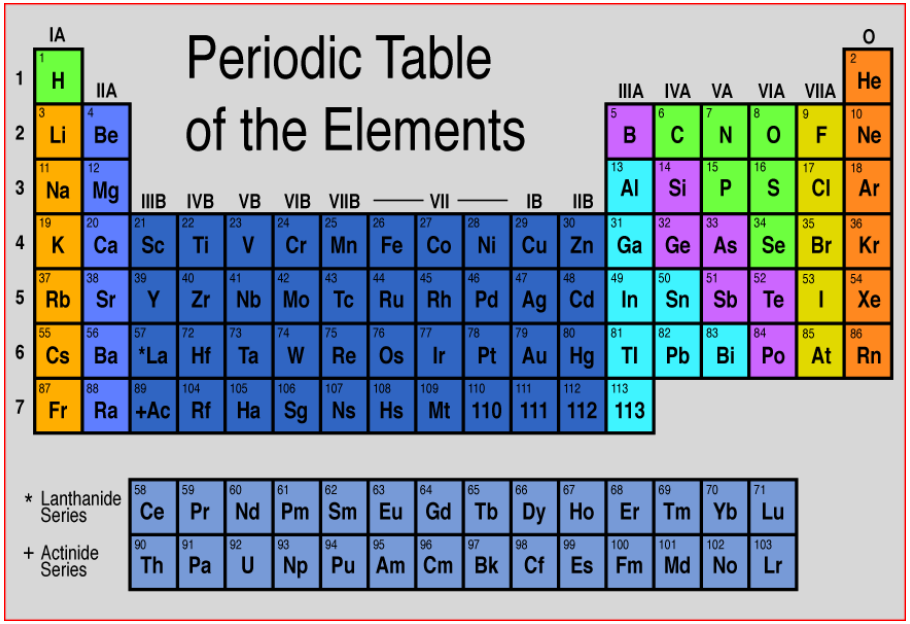
Democritus, Greek philosopher ~ 400 B.C:

“All matter is made up of very small indivisible elements”

He called them ‘atomos’.

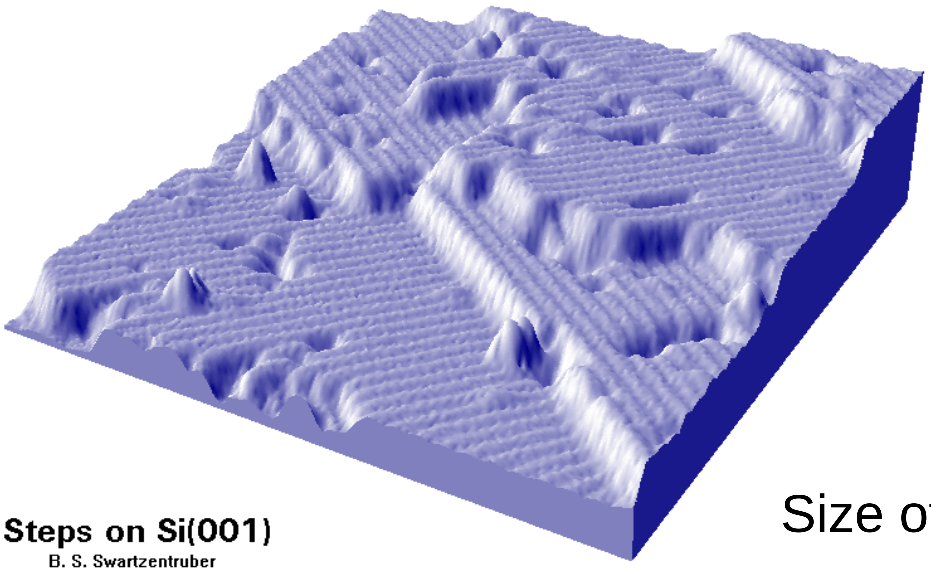
19th century chemistry confirms: there are only 92 different ‘elements’, from hydrogen H to uranium U.

Everything around us is built from combinations of these elements.

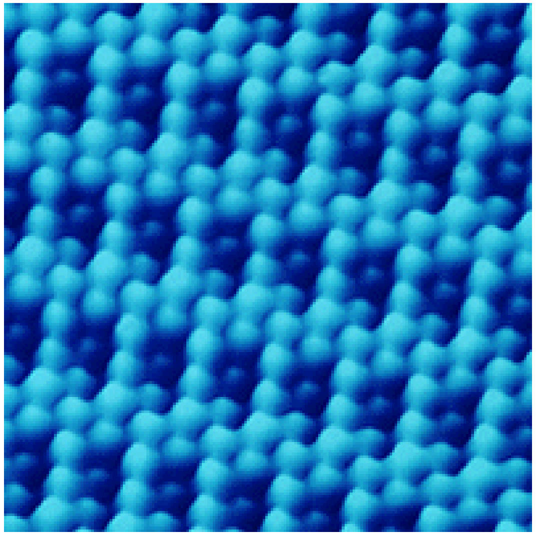


Atoms

Today: we can make atoms visible



Steps on Si(001)
B. S. Swartzentruber
Sandia National Lab



U of Oregon Chemistry

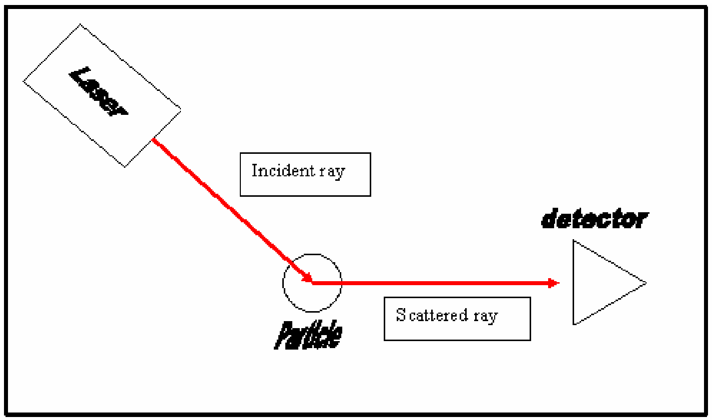
Size of the smallest atom (hydrogen):

0.000 000 000 1 m (meter)
= 10^{-10} m = 1 Angstrom

How is it possible to see such tiny structures?

Scattering Experiments

Our vision: the eye collects light reflected from objects and our brain processes the information

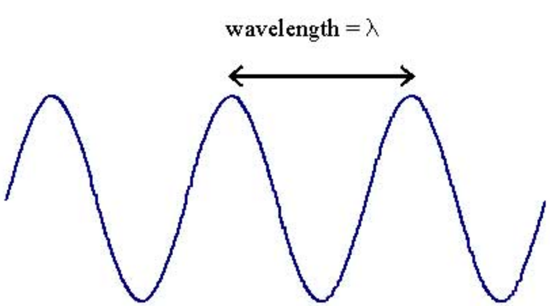


Light: wavelength 4000 – 7000 Angstrom, too large to see an atom.
Better: X-rays, electrons

Use this principle:
Shoot a ray of light or particles at an object.
Measure the scattered rays with a detector.

Resolution of the probe (light, particle) is important:

The wavelength must be smaller than the size of the structure to probe.

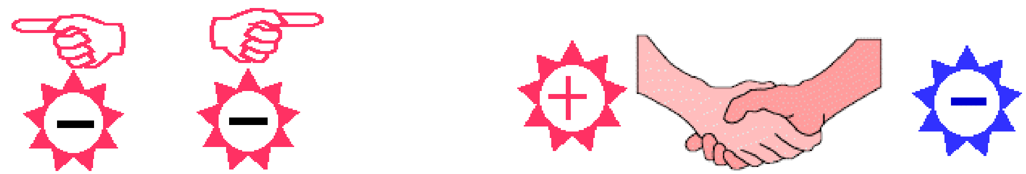


Electromagnetism

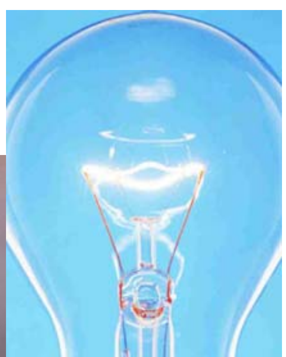
Electric phenomena:

Two kind of charges:
plus and minus

The forces between them
lead to electric currents.

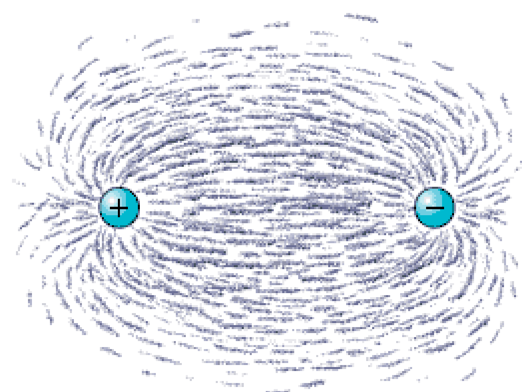


Equal charges repel each other
Opposite charges attract each other



Electric force acts over a
distance even in empty space:

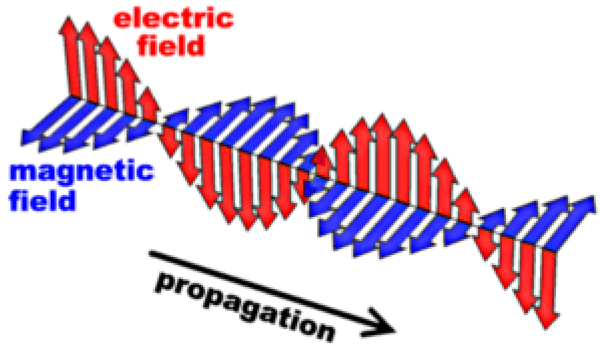
→ Electric field

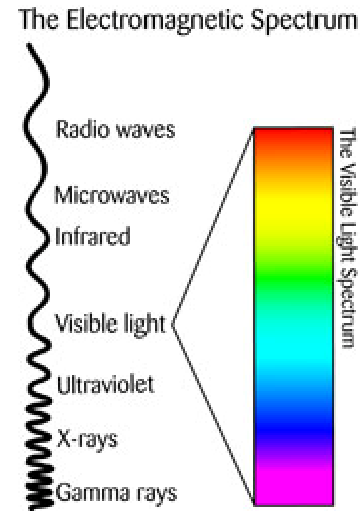


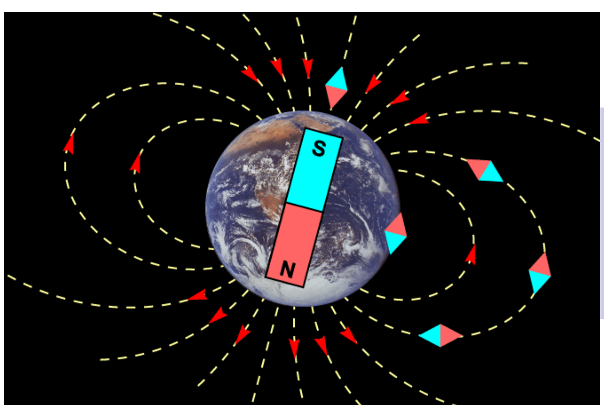
Electromagnetism

Moving electric charges produce magnetic fields.
Accelerated electric charges produce electromagnetic waves.

Electromagnetic waves = a special combination of electric and magnetic fields that can travel over long distances (e.g. radio waves, light, X rays)







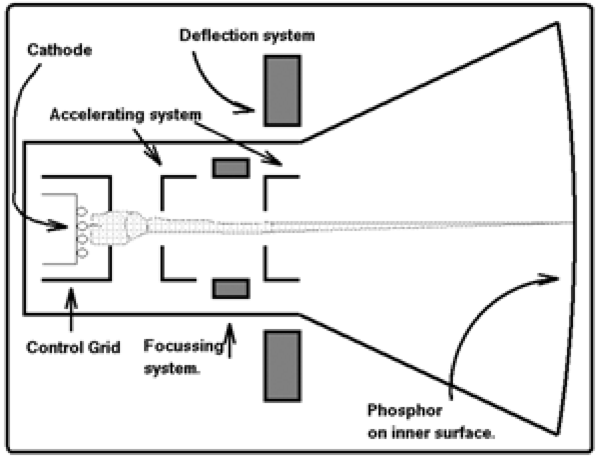
Electromagnetism describes electricity, magnetism and light

Electrons

What is electric current?
In wires there seems to be a flow of very small quantities of negative electric charge carried by tiny particles.

They are called electrons e^{-}.

In fact these 'quanta' can be extracted from metals by heating them up $\rightarrow$ cathode rays.



Basic properties of electrons, measured around 1900:

Electric charge is –e. e = 1.6×10^{-19} C is called the fundamental charge.

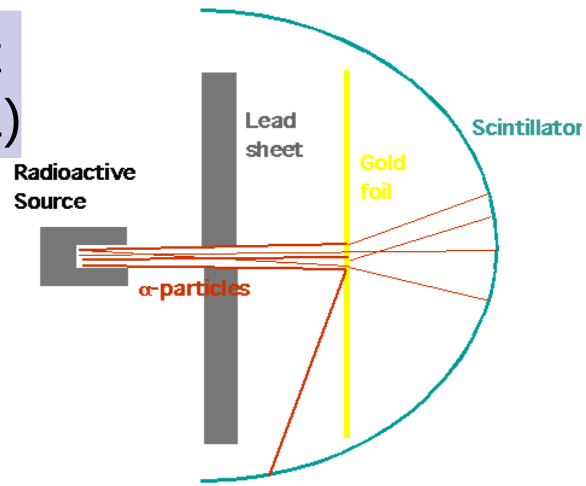
Mass = 1/2000 u. 1 u is the mass of the hydrogen atom.

J. J. Thomson (1897): Electrons are small parts of atoms.
The first 'subatomic' particle was discovered.

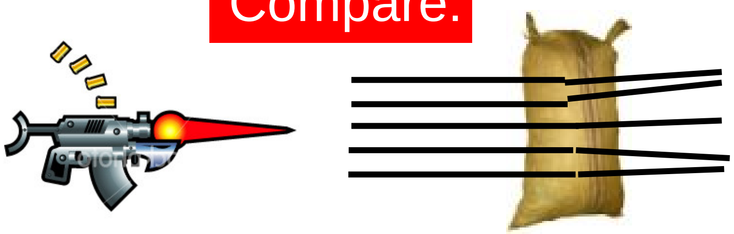
Taking a Look inside an Atom

Atoms are neutral. If they contain electrons there must be an equal amount of positive charge. How does an atom look on the inside?

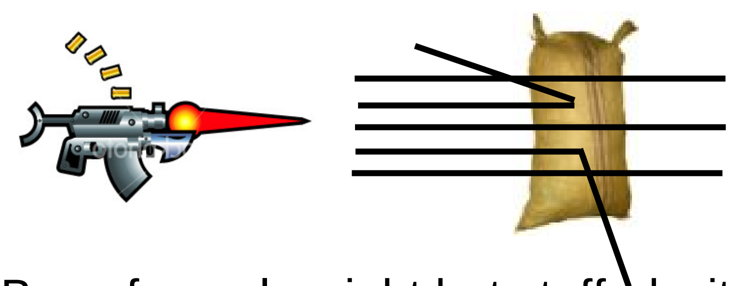
Scattering Experiment of E. Rutherford (1911)



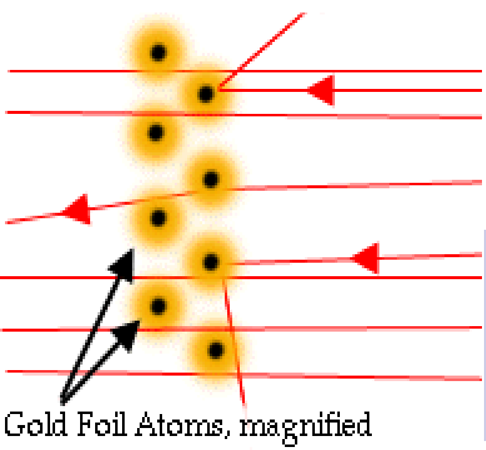
Compare:



Bag of beans



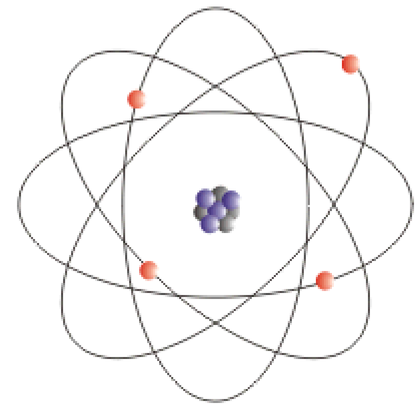
Bag of equal weight but stuffed with cotton and a few small lead beads



Rutherford’s result is similar to the second scenario!

The positive charge in an atom and most of its mass is concentrated in a tiny, very dense center, the nucleus.

The Nucleus

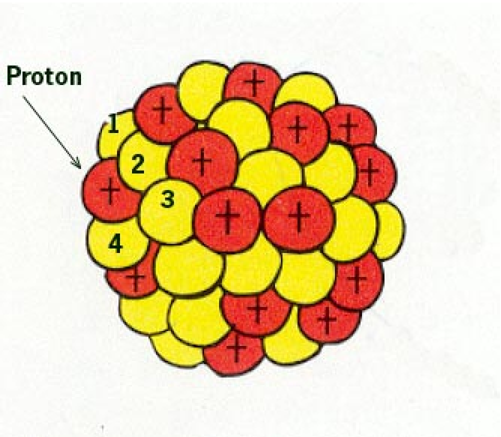


More than 99% of the mass of an atom is in the nucleus, which is more than 10,000 times smaller than the atom, about 1 – 10 fm (Fermi).
1 fm = 10^{-5} Angstrom = 10^{-15} m.

A cloud of electrons orbits the nucleus, held in place by the mutual attraction of the electric charges.

Most of the atom is just empty space!
But with a strong electromagnetic field present.

Nuclei are made up of two particles:
Protons p: positive charge +e, mass ≈ 1u
Neutrons n: neutral, roughly the same mass as p



Protons and neutrons are kept together by a new force: the *strong force*.

Particles

We distinguish particles by their …

participation in strong interactions
YES: they are called *hadrons*
e.g. proton, neutron
NO: they are called *leptons*
e.g. electron

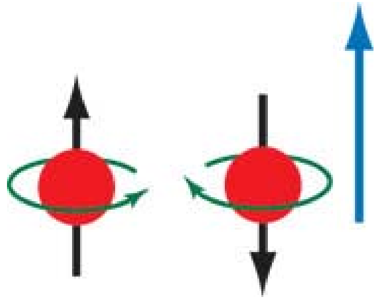
electric charge
positive or negative
usually in multiples of e

mass
usually measured in electronvolts (eV)
1 u ≈ 0.939 GeV (Gigaelectronvolts, Giga = Billion)

spin
= Quantized angular momentum
(can take values $0\hbar$, ½ $\hbar$, 1 $\hbar$, 3/2 $\hbar$, 2 $\hbar$, etc)
Electrons, protons, neutrons: spin ½ $\hbar$

Particles with integer spin are called *bosons*.

Particles with half-integer spin are called *fermions*.



Electrons, protons and neutrons are fermions.

Particles

Bosons like the company of other particles of their kind.

Fermions avoid to be in the same state as other particles of their kind.

Relativistic Quantum Theory predicts that for each fundamental particle there is an *antiparticle* with the same mass and spin, and with opposite charge.

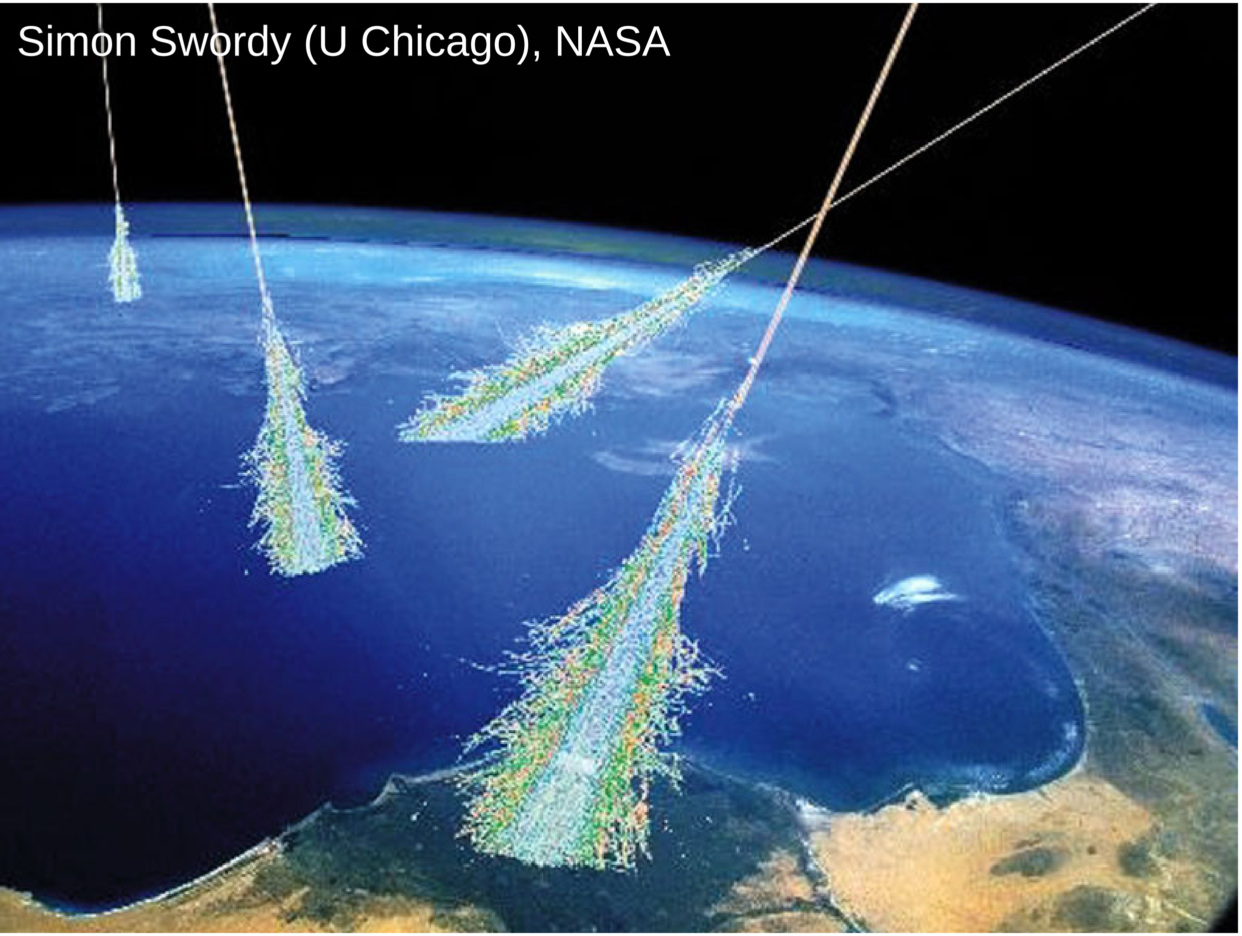
E.g. antiproton $\bar{p}$, anti-electron (positron) e^+.

How about the size?

Protons and neutrons (and all hadrons) have a diameter of roughly 1 fm.

Electrons are pointlike to our best knowledge. Their Size appears to be smaller than 0.0001 fm (10^{-19} m).

Cosmic Rays



High energy particles, mostly protons, of cosmic origin (sun, supernovae, colliding galaxies)

Energy up to 10^{11} GeV

Because of $\boxed{E = mc^2}$ energy can be converted to mass (matter!) and vice versa.

By scattering off atomic nuclei in the atmosphere, the energy of the ray is converted into a shower of many secondary particles.

More Particles

1930s and 40s: more particles were found in cosmic ray showers.

The *muon* μ^- (and its antiparticle μ^+)

The muon is a fermion with spin ½ . It does not participate in the strong interaction, so it is a lepton. It behaves like a heavier brother of the electron.
Mass 0.106 GeV
(electron: 0.000511 GeV)

The *pion* triplet π^+, π^0, π^- (charge +e, 0, –e)

Pions are bosons with spin 0. They feel the strong force, so they are hadrons.
Mass = 0.139 GeV
(π^0 slightly below)

These particles are unstable.
They decay into lighter particles, e.g.

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

anti-electron neutrino   muon neutrino

Neutrinos ν_e, ν_μ and their antiparticles $\overline{\nu}_e$, $\overline{\nu}_\mu$

They are fermions with spin ½.

Neutrinos

Neutrinos are ‘ghost’ particles.

That means they are almost undetectable!

They don’t have electric charge.

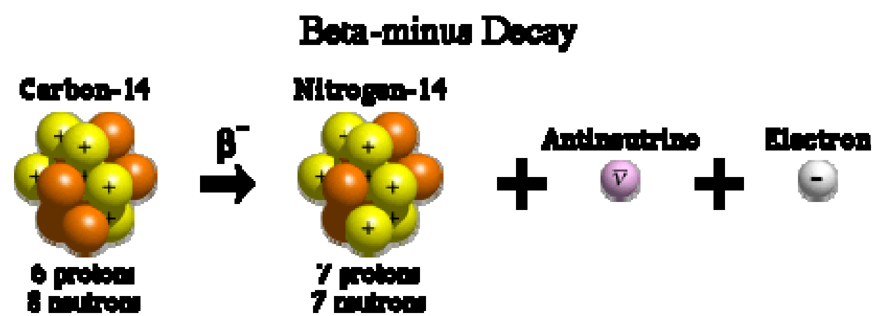
They don’t feel the strong force

They have an extremely small mass (or none at all?)

How can they interact at all with other particles?
This is a new force at work. It is called the *weak force*.
All particles discussed so far feel the weak force.

Neutrinos and anti neutrinos have also been found in β-decays of nuclei:

$$n \to p + e^- + \bar{\nu}_e$$

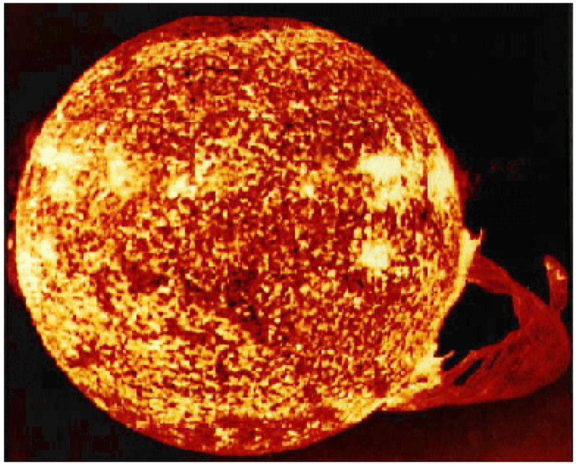


Btw: what we call β-radiation are the emitted electrons!

Neutrinos and the Weak Force

They are produced abundantly in the sun in the hydrogen-helium fusion.

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$



Have you ever noticed?

More than 1000 billion neutrinos from the sun pass through your body every second!
They rarely interact.

Neutrinos are also leptons.
Most of the time the processes of the weak force involve pairs of leptons belonging to one family (or generation).

1st generation

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$$

2nd generation

$$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$$

A third generation with the τ and ν_τ was discovered later.

$$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

The Weak Force?
It stays in the family (mostly).

Quantum Fields

M. Planck (1900) suggested that energy in light comes in small packets called ‘quanta’.

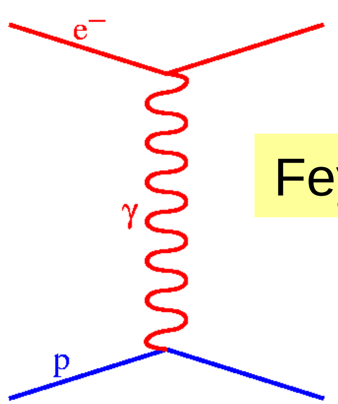
Energy of one quantum $\boxed{E = h\nu}$

ν = frequency

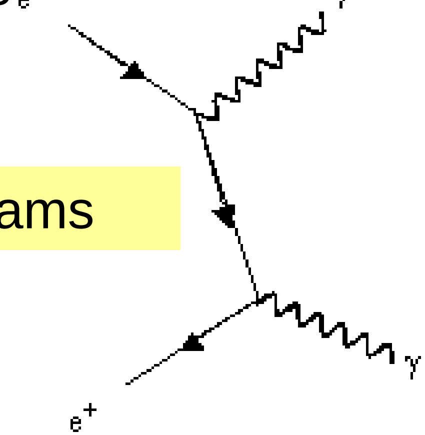
These quantum packets behave like particles.
The electromagnetic field can be described by the action of these force carrier particles, called *photons* γ.

Photons are bosons with spin 1 and they are massless. They ‘couple’ to electric charges and have no electric charge themselve

Force carriers transmit forces by being exchanged between particles.



Feynman diagrams



Electron + proton interacting

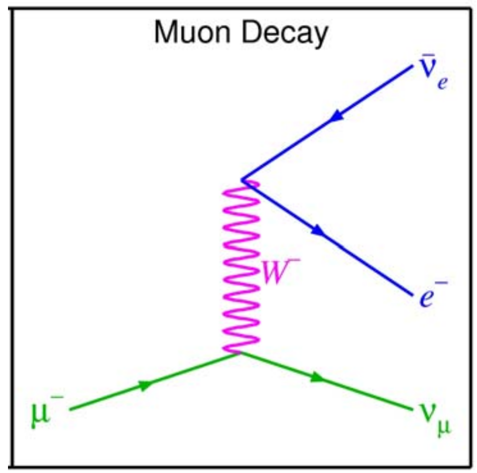
Electron-positron annihilation $e^+ + e^- \rightarrow 2\gamma$

Electroweak Force

It could be shown that the weak force and the electromagnetic force are two aspects of one unified *electroweak force*.

There are 3 spin-1 bosons which are force carriers of the weak force, the W^+, W^- and Z^0 bosons which are very heavy. They couple to all fermions.

Feynman diagram for muon decay



Boson with mass 0 (e.g. photon):
force ~ 1/distance^2, infinite range

W,Z bosons with large mass:
Force acts only over distance < 0.01 fm

BOSONS

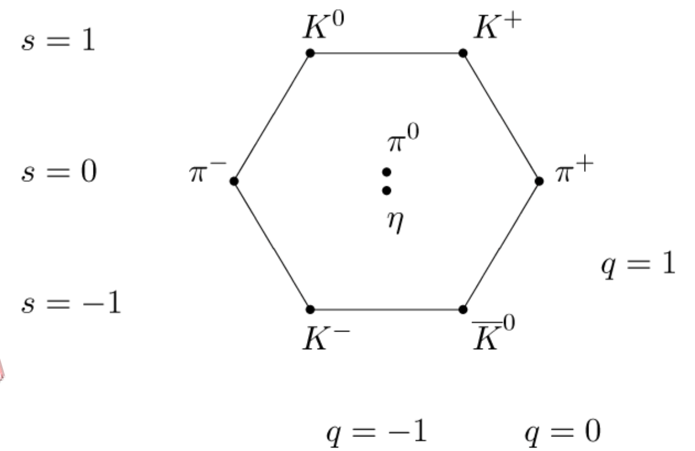
Unified Electroweak spin = 1

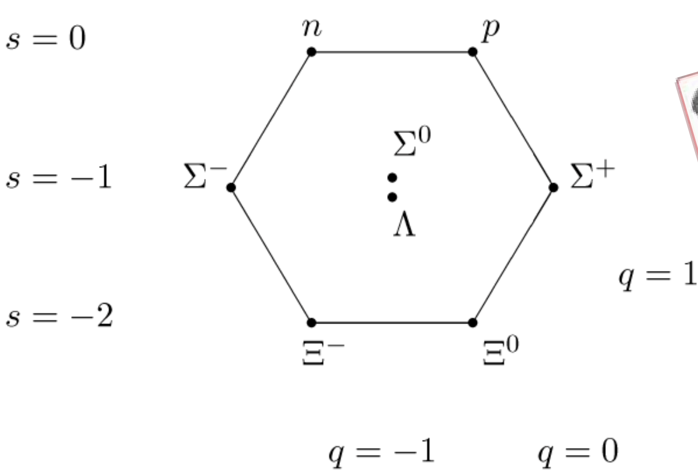
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

The Hadron Zoo

After 1950 powerful accelerators were built, not only to test the structure of known particles, but to produce new ones.

They found many more hadrons (i.e. strongly interacting fermions). Too many!
Maybe they are not elementary particles?



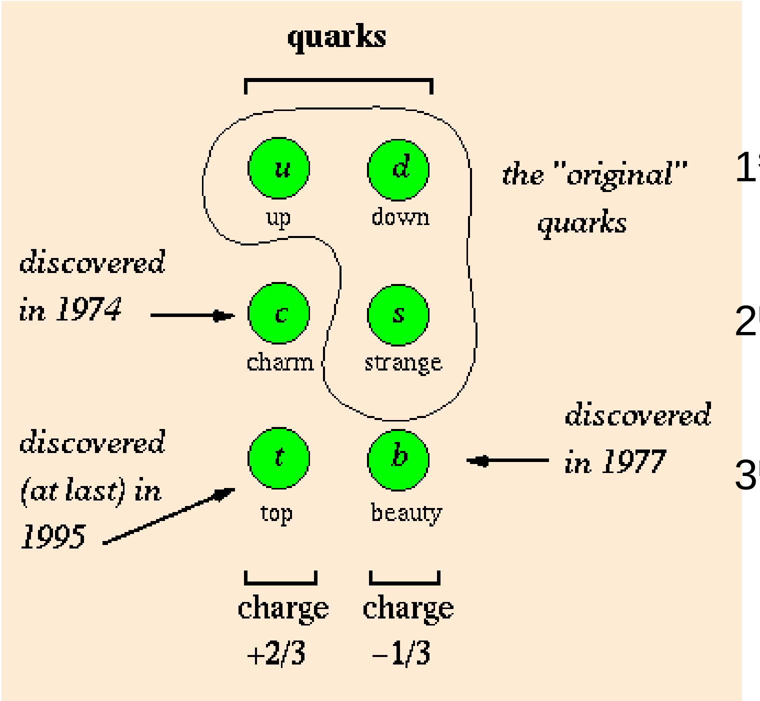


They can be grouped into multiplets.
Similar to the periodic system.

M. Gell Mann (1962): the systematics can be understood if hadrons consisted of combinations of fundamental fermions. He called them *quarks*.

Quarks

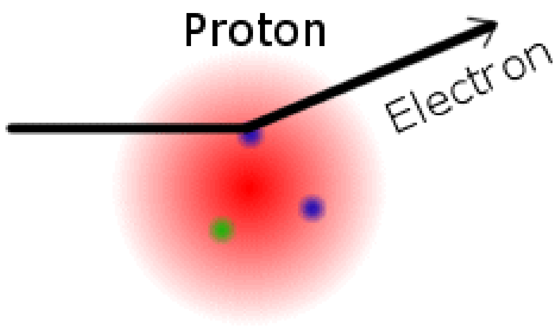
1968 a Rutherford-like experiment (deep inelastic scattering) confirmed that there are indeed quarks inside a proton.



1st generation

2nd generation

3rd generation



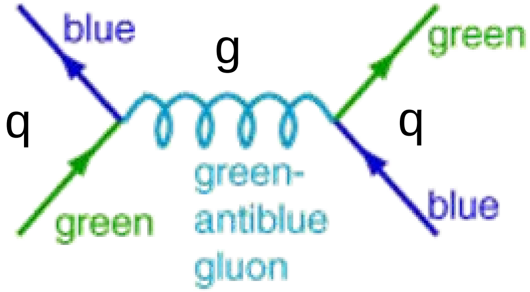
There are six quarks in 3 generations:
(up,down)
(charm, strange)
(top,bottom)
+ their six antiquarks

Increasing mass from 0.002 GeV (up) to 174 GeV (top).

Surprise: they have fractional electric charges +2/3 or -1/3. They feel both the weak and strong force.

Gluons

The strong interaction between quarks through exchange of another spin-1 boson: the *gluon* g.



'Charges' for the strong force are called color charges. There are three of them and each quark can carry all 3:
'red', 'green' and 'blue' (+ 3 anti colors for antiquarks)

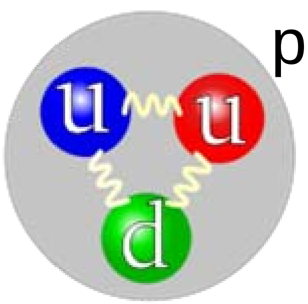
Careful: this is not the same as color in common language!

Gluons couple to the color of a particle.

Two kind of hadrons ('quark atoms') exist:

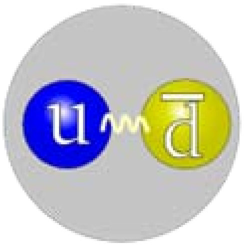
Quark + Antiquark = *Meson*
(e.g. pions)

3 Quarks = *Baryon*
(e.g. proton, neutron)



p

Hadron are color neutral: Colors of the quarks add up to 'white'

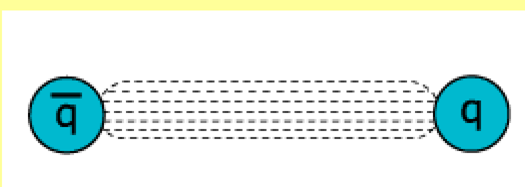


π^+

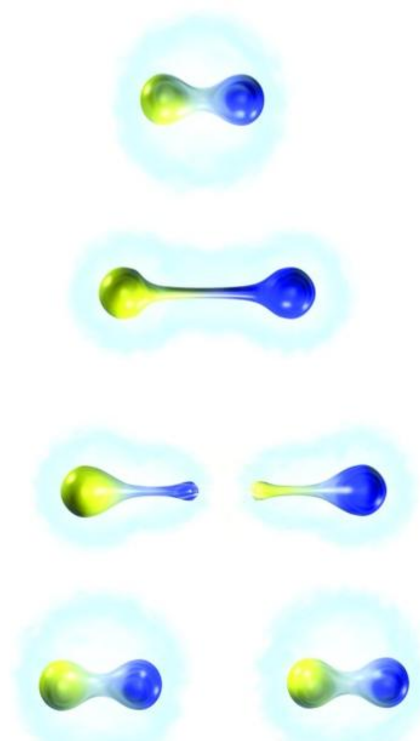
The Strong Force

The gluon itself carries color charge.
Gluons feel the strong force they themselves provide!
This has very interesting consequences.

Gluons form ‘flux tubes’ between quarks which act like rubber bands.



To pull this quark-antiquark pair apart you need to spend more and more energy.



Confinement: Quarks and gluons have <u>never</u> been observed outside of hadrons.

Remember the electric field becomes weaker with increasing distance!

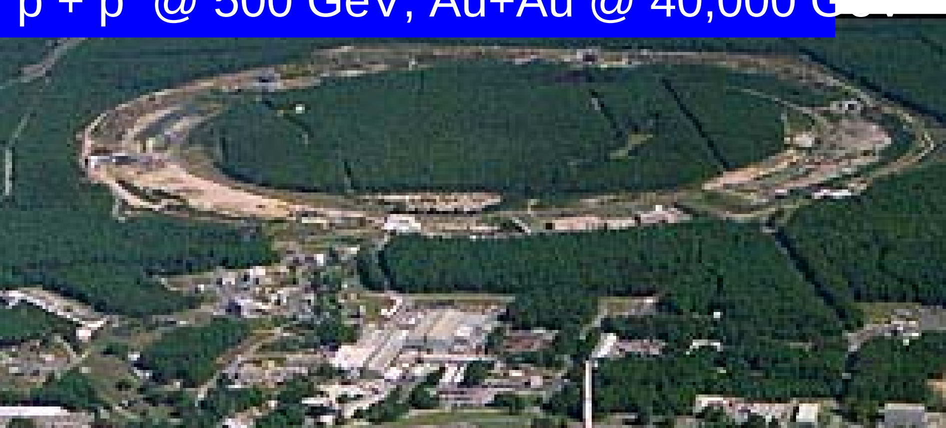
Breaking of a flux tube: create a new $q\bar{q}$ pair, never single quarks

Accelerators

Particle accelerators at the frontier.

Latest discoveries of elementary particles:

ν_τ (Fermilab, 2000)
t quark (Fermilab, 1994)
$W^\pm$, Z^0 (CERN, 1983)



Rules for the Subatomic World

Reactions among particles, like chemical reactions, obey certain rules.

The most important rules are conservation laws. Conservation of a quantity means that one must have the same amount before and after the reaction.
Important examples:

Energy (but not mass!)

A loss of mass has to be compensated by an equal amount of kinetic energy.

Electric Charge

The number of positive charge minus the number of negative charge is constant.

Color Charge

Works similar to electric
charge. Net charge can not be created or

Baryon Number

Count quarks as +1/3, antiquarks as -1/3, baryons as 1, antibaryons as –1.

Thus it is possible to create quark-antiquark pairs or lepton-antilepton pairs from energy and vice versa.

Lepton Number

Count leptons as +1, their antiparticles as –1.

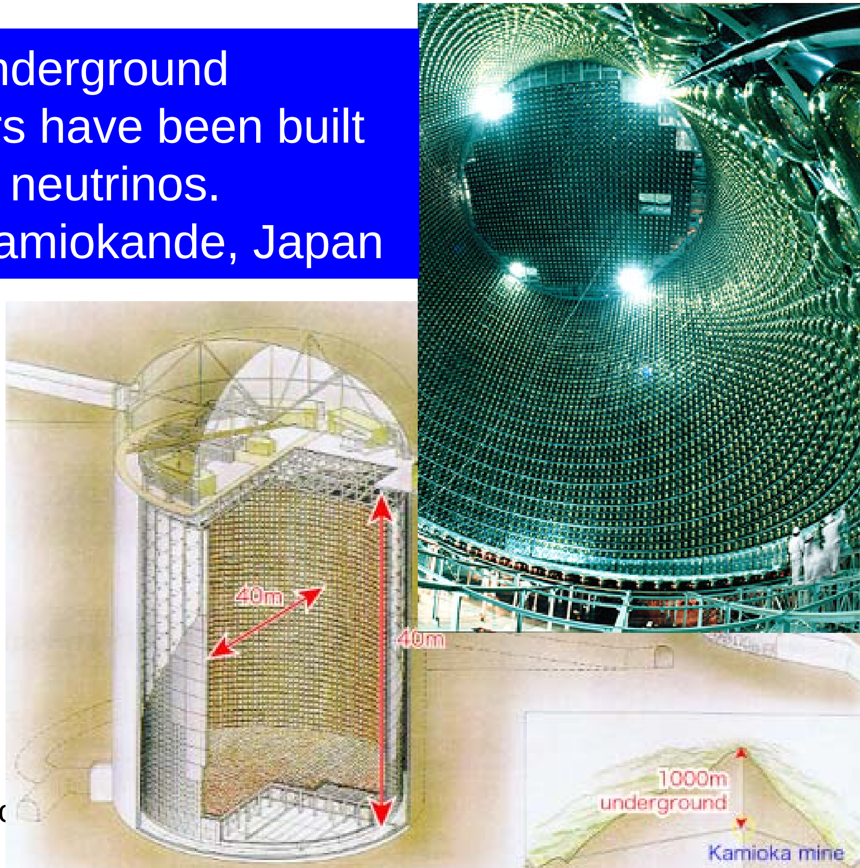
Neutrino Mass

For a long time, neutrinos were suspected to have no mass at all.

But if neutrinos do have masses, the 3 generations of neutrinos, ν_e, ν_μ, ν_τ, can switch their identity while traveling through space due to a quantum effect.

$$\nu_\mu \rightarrow \nu_\tau \qquad \nu_e \rightarrow \nu_\mu \qquad \nu_\mu \rightarrow \nu_e$$

Huge underground detectors have been built to catch neutrinos.
Here: Kamiokande, Japan



Such neutrino oscillations have been observed in 1998.

Still neutrino masses are very small: The mass of ν_e is more than 100,000 times smaller than the mass of the electron.

The Standard Model

What we have described so far is called the Standard Model of Particle Physics.

The fermions (quarks and leptons) are the building blocks of matter.

A set of bosons are the force carriers for the electromagnetic, weak and strong interactions.

<u>Compare the interactions:</u>

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

The 4th force in nature, gravity, is usually not considered to be a part of the Standard Model. It is EXTREMELY weak.

The Standard Model

BOSONS
force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W⁻	80.39	–1
W⁺ W bosons	80.39	+1
Z⁰ Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

6 fermions and 6 leptons come in 3 identical generations
(only masses are different)
Plus they have antiparticles.

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, …

Leptons spin =1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Leptons and quarks feel the weak force. Only quarks have color charges and feel the strong force.

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	**Name**	**Quark content**	**Electric charge**	**Mass GeV/c²**	**Spin**
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Quarks are confined into colorless objects, the hadrons.

Hadrons can be quark-antiquark systems (mesons) or 3 quark systems (baryons)

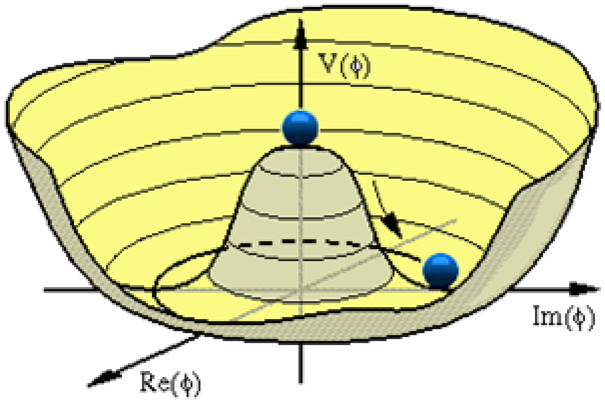
Mesons $q\bar{q}$ Mesons are bosonic hadrons These are a few of the many types of mesons.					
Symbol	**Name**	**Quark content**	**Electric charge**	**Mass GeV/c²**	**Spin**
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Of the 24 quarks and leptons in the Standard Model, only
3 are necessary to build atoms and all chemical elements:
u, d, e^-

The Higgs Boson

One particle is left to discuss: the *Higgs Boson* is part of the Standard Model, but it is very special.

Higgs Mechanism:
A field fills all of space because of a mechanism called spontaneous symmetry breaking. It 'sticks' to particles, making it 'harder for them to move'. This is what gives quarks and leptons their mass.

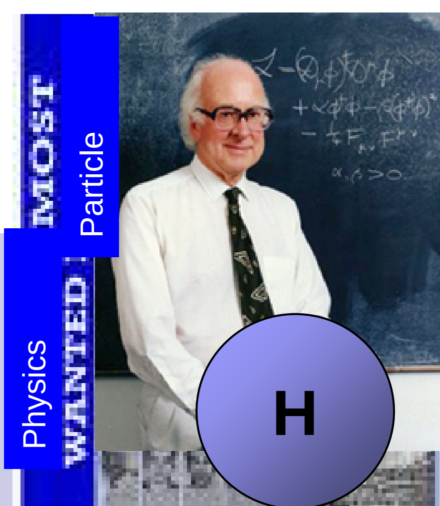


Spontaneous symmetry breaking

Credit: CERN

Similar to the celebrity effect in a crowd.

As a consequence, there should also be a spin-0 boson, the Higgs boson. It has not been found yet.



The End

The animation *Secret Worlds: The Universe Within* can be found on the website of the National High Magnetic Field Laboratory at Florida State University.

http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/

Credit: Florida State University. A Java plugin for the browser is necessary to watch the animation.