Saturday Morning Physics -- Texas A&M University

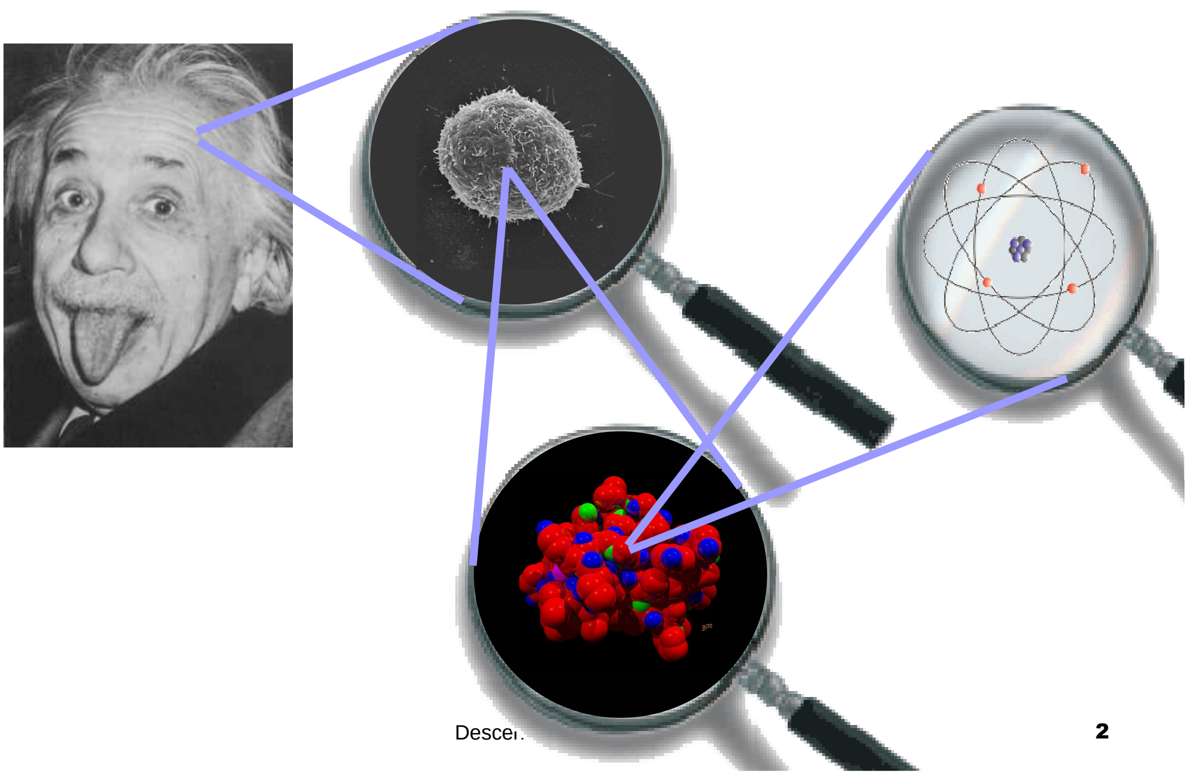
Descent into the Proton

A Journey Inside an Elementary Particle

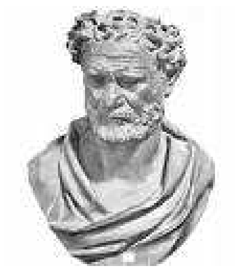
Dr. Rainer J. Fries

March 22, 2008

Zooming in on the World around us



Atoms



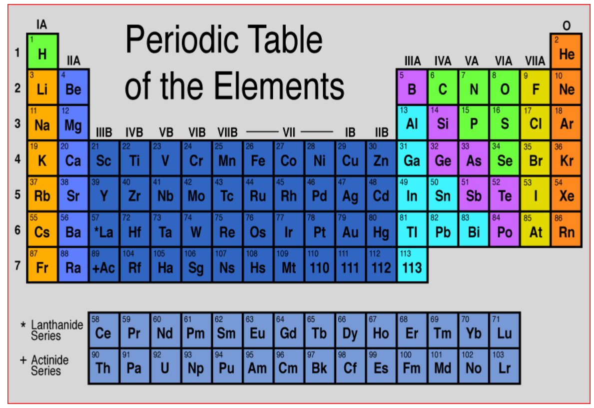
19th century chemistry confirms:
there are only 92 different 'elements',
from hydrogen H to uranium U.

Everything around us is built from combinations of these elements.

Democritus, Greek philosopher ~ 400 B.C:

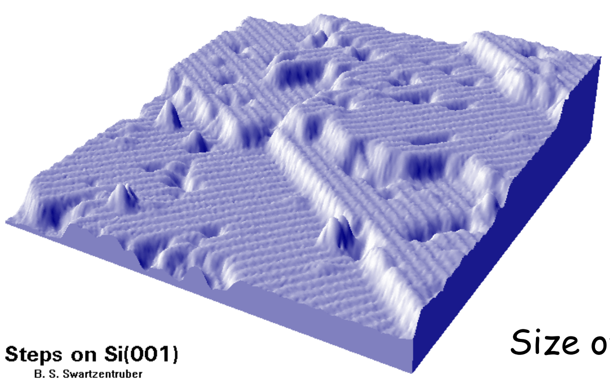
"All matter is made up of very small indivisible elements"

He called them 'atomos'.

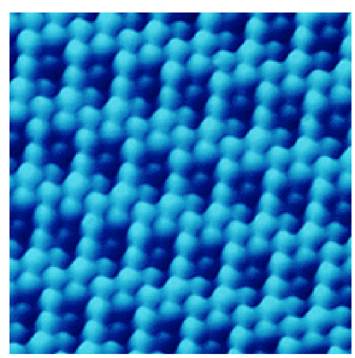


Atoms

Today: we can make atoms visible



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



U of Oregon Chemistry

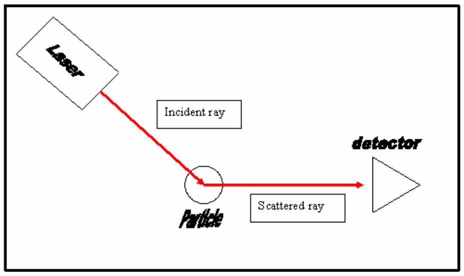
Size of the smallest atom (hydrogen):

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

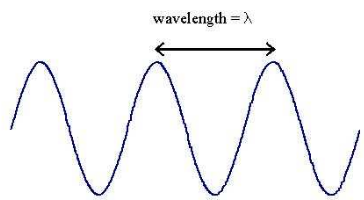


Light: wavelength 4000 – 7000 Angstrom, too large to see an atom.
Better: X-rays, electrons

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.

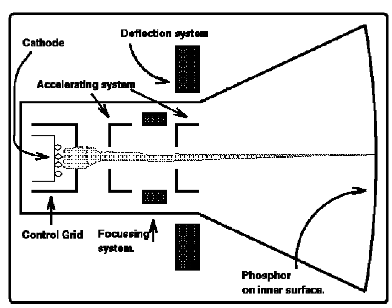


Electrons

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 $-e$. $e = 1.6 \times 10^{-19}$ C is called the fundamental charge.

Mass = 1/2000 u = 511 keV. 1 u is the mass of the hydrogen atom.

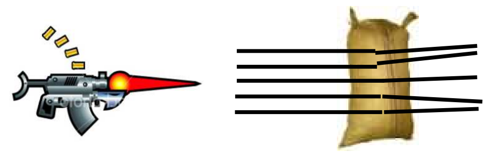
J. J. Thomson (1897):
Electrons are small parts of atoms.
The first 'subatomic' particle was discovered.

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?

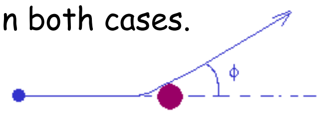
Compare the following two "scattering experiments":

Professional scientist, closed lab, do not attempt!

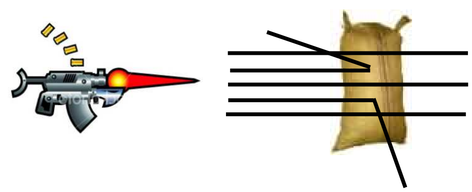


1) Shooting at a bag of beans

Obviously the possible scattering angles of the bullets are different in both cases.



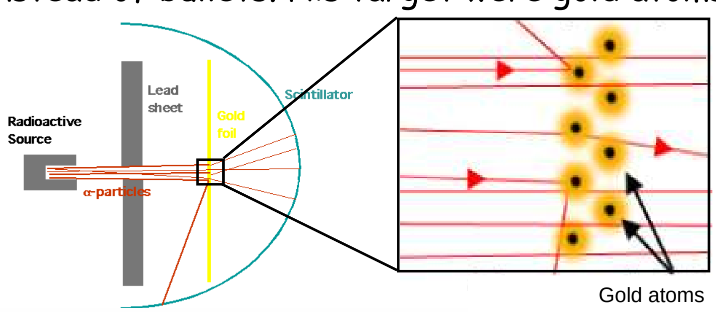
1) Only small angles possible.
2) Some bullets are scattered at large angles.



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

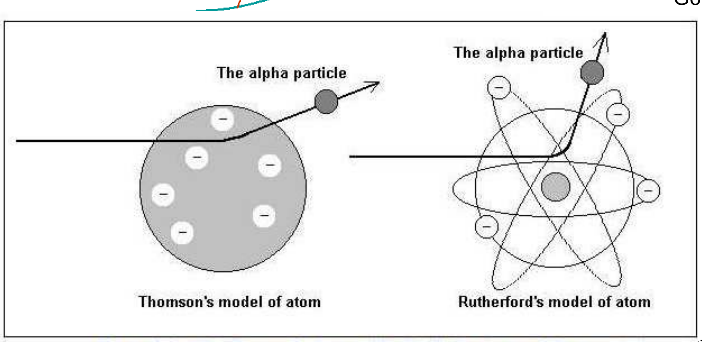
Taking a Look inside an Atom

In 1911 E. Rutherford did this famous experiment with α-particles instead of bullets. His target were gold atoms.



Gold atoms

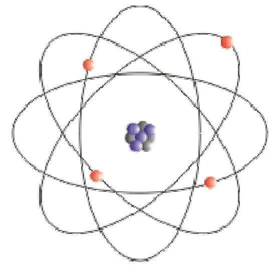
Rutherford's result was similar to the second scenario!



The models of the Thomson's atom and Rurtherford's atom; and the expected aberrations of alpha particle in both cases.

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

The Nucleus

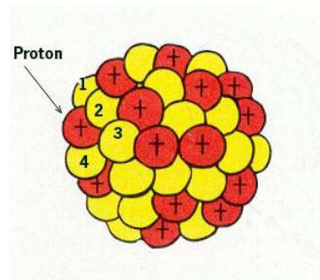


More than 99% of the mass of an atom is in the nucleus, which is more than 10,000 times smaller than the atom, about 1 – 10 fm (Fermi).
1 fm = 10^{-5} Angstrom = 10^{-15} m.

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

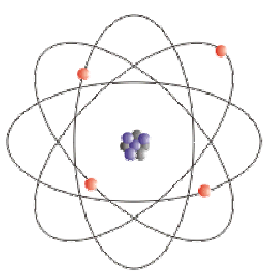
Most of the atom is just empty space!
But with a strong electromagnetic field present.

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*.

Atoms: A Modern View

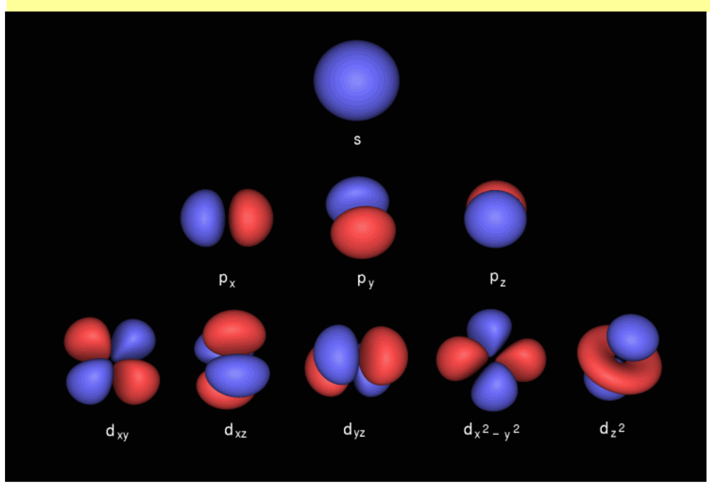


Rutherford, Bohr

Heisenberg
Schroedinger

Quantum mechanics tells us that electrons can not be localized. Only a probability can be given for their current position.

⇒ Atomic orbitals.



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

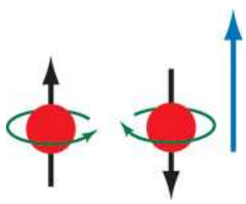
electric charge
positive or negative
usually in multiples of e

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

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

Particles with integer spin are called *bosons*.

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



Electrons, protons and neutrons are fermions.

The Hadron Zoo

In 1940 only 5 elementary particles were known: proton, neutron, electron, muon and positron. With the advent of accelerators at the end of the decade a big 'zoo' of hadrons was discovered.

Remember: hadrons are subject to the strong force, like the proton

They could be grouped into one of two categories:

- Heavier baryons, whose total number is always conserved. E.g. protons, neutrons

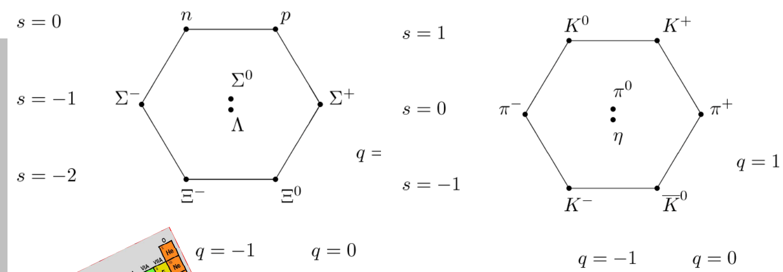
- Lighter mesons, which can decay into particles which are not hadrons. E.g. pions, kaons

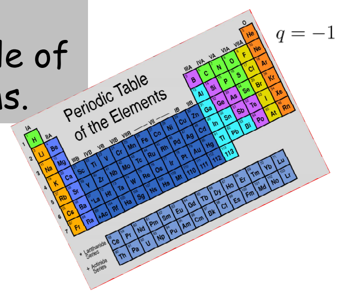
Too many! Maybe hadrons are not elementary particles after all?

The Hadron Zoo

Eventually it was found that hadrons with similar properties can be grouped into multiplets.

Compare: periodic table of the elements for atoms.





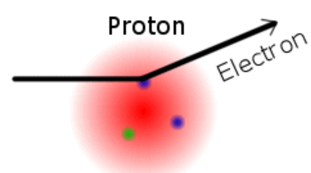
Gell-Mann & Zweig (1964): the systematics of hadrons could be understood if hadrons consisted of combinations of smaller, more fundamental particles. Those must be fermions (spin-$\frac{1}{2}$) and have fractional charges.

Gell-Mann called them *quarks*. Nobody believed them.

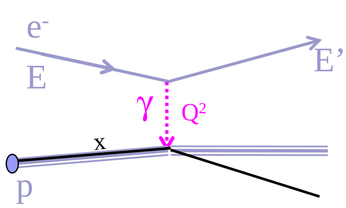
Deep-Inelastic Scattering (DIS)

How could this hypothesis be tested?
A new Rutherford experiment with better resolution!

Introducing: deep-inelastic scattering (DIS),
shoot electrons at protons with E_{cm} > 1 GeV



Measurement:
deflection angle θ
final electron energy E'



E.g. proton as a whole: x=1.

If it consisted of three equal parts with the same energy, each of those would have x = 1/3.

θ and E' can be rewritten as two quantities known as x and Q^2.

x = fraction of the proton energy carried by what is hit inside the proton.
Q^2 = resolution of the photon.

Deep-Inelastic Scattering (DIS)

DIS scattering formula:
(cross section as function of θ and E')

$$\frac{d\sigma}{dE'd\Omega} = \left(\frac{\alpha\hbar}{2E\sin^2(\theta/2)}\right)^2 \left[\frac{2F_1(x,Q^2)}{M}\sin^2(\theta/2) + \frac{2MxF_2(x,Q^2)}{Q^2}\cos^2(\theta/2)\right]$$

"Structure functions" F_1 and F_2 know about the structure of the proton.

Different predictions had been made.

For the quark model (i.e. proton is a loose collection of point-like spin-½ fermions):

1) F_1, F_2 don't depend on Q^2 (Bjorken scaling)

2) F_1, F_2 are not independent: $2xF_1 = F_2$ (Callan-Gross relation)

The Discovery of Quarks

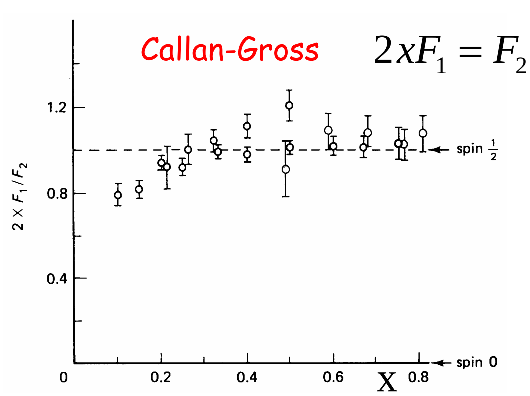
The verdict (SLAC, 1968)
SLAC = Stanford Linear Accelerator Center

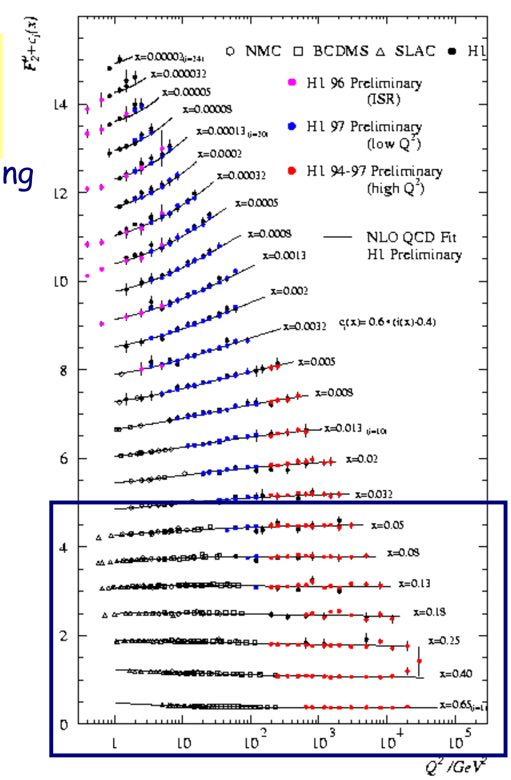
The Winner is

...

the Quark Triplet!

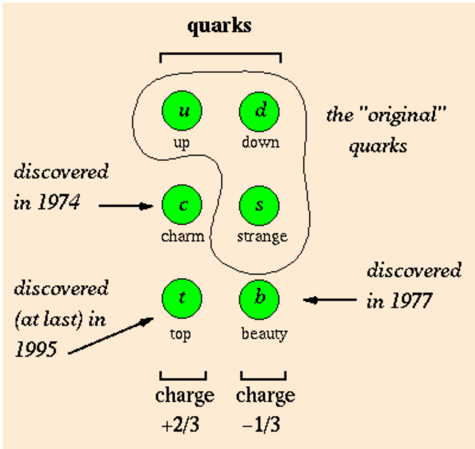
Bjorken scaling





Quarks

3 different quarks were initially found: Up, Down and Strange.
Three more were found later on.



1st generation

2nd generation

3rd generation

We know that there are only 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 do have fractional electric charges +2/3 or -1/3. They feel both the weak and strong force.

Quantum Chromodynamics

How do quarks interact and bind together?

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

Experimental result: each quark seems to exist in three varieties. The strange new feature was called color.

Each quark has one of three colors: 'red', 'green' or 'blue'
(+ 3 anti colors for antiquarks)

u u u

1972: the theory of *Quantum Chromodynamics* is born:

Quarks interact through a new kind of particle, called the *gluon*. The gluon transmits the strong force, just as photons transmit the electromagnetic force.

It was realized that gluons can be described by a strange theory already written down in 1955 by Yang and Mills (above).

Gluons

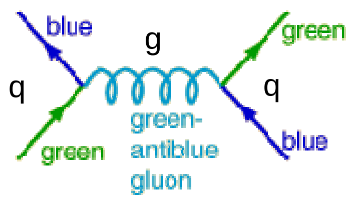
Color is the 'charge' for the strong force, i.e. gluons couple to this color charge

(just as photons couple to electric charge to transmit the electromagnetic force)

Gluons themselves also carry color. Thus gluons couple to themselves!

This is a direct result of the Yang-Mills theory.

There are 8 different color charges possible for a gluon
(3 color)x(3 anti-color)-'white'



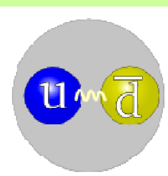
Color is conserved in the coupling.

Hadrons = Bound States

Experimental fact: all hadrons are color neutral.

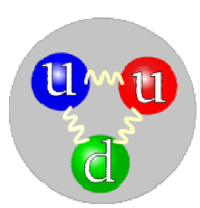
I.e. the color of the quarks and gluon inside has to add up to 'white'.

- Meson = quark + antiquark



π^+

- Baryon = 3 quarks



p

Those quarks are called the valence quarks of a hadron.

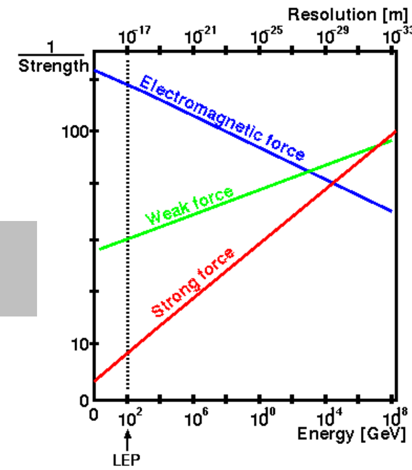
E.g. the valence quark structure of the proton is *uud*

Asymptotic Freedom

Puzzle: if the strong force is "strong", why does the quark model (i.e. hadron = loose collection of quarks) work in deep-inelastic scattering?

Gross, Wilczek, Politzer (1974):
QCD asymptotically free.

> The strength of the color coupling increases
> further away from the color charge.

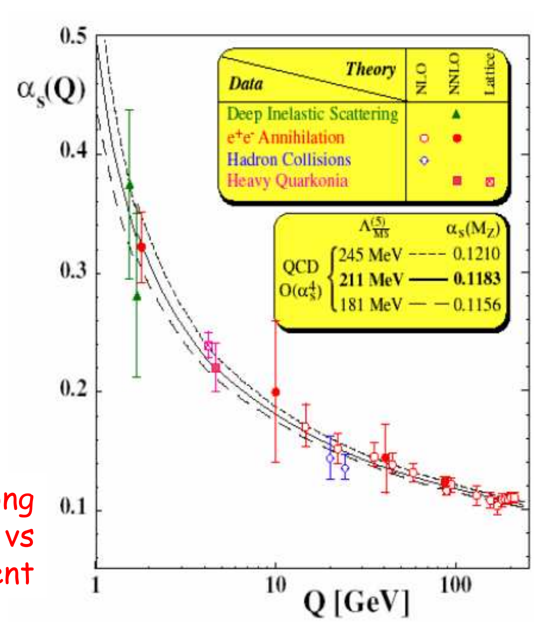


Strength of a charge is not really constant in quantum field theories, it depends on energy.

Asymptotic Freedom

At high energies (or when very close) quarks and gluons (partons) interact weakly.

At low energies (or when far apart) quarks and gluons interact strongly.

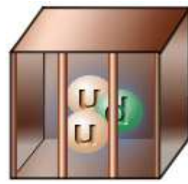


Running of the strong coupling: theory vs experiment

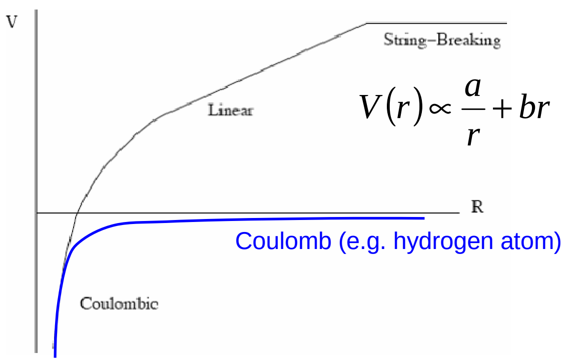
Confinement

QCD exhibits another fantastic feature: confinement. No free color charge can exist in the vacuum (remember hadrons are all color neutral.

Potential energy of two quarks: Coulomb-like at small distances, linear at large distances.



Quarks and gluons have <u>never</u> been observed in the vacuum.



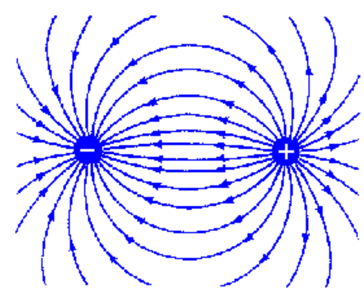
Confinement has not yet been fully understood.

It has been named one of the outstanding mathematical problems of our time. The Clay Foundation will pay you $1,000,000 if you prove it!

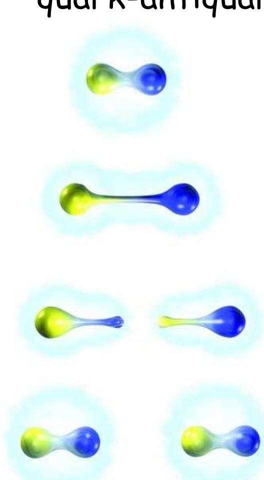
http://www.claymath.org/

Confinement

- The QCD vacuum is diamagnetic and repels field lines. They are squeezed into flux tubes.
- If enough energy is pumped into such a “gluon string” it breaks and a quark-antiquark pair is created.

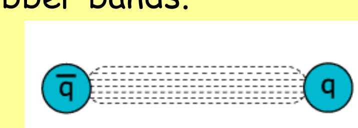


Compare: two electric charges



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

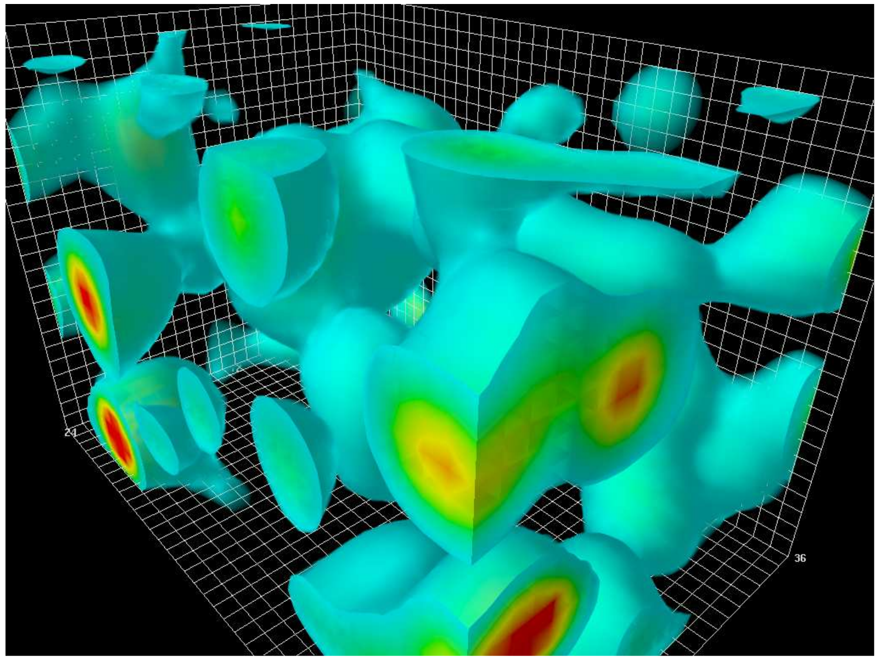
Gluons moving over large distances form ‘flux tubes’ between quarks which act like rubber bands.



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

QCD Vacuum

Modern interpretation of a vacuum:
Constant fluctuations of particles coming into existence and annihilating again

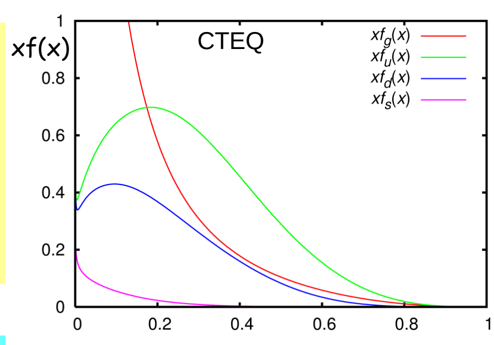


D. Leinweber (Adelaide)

A Modern Perspective

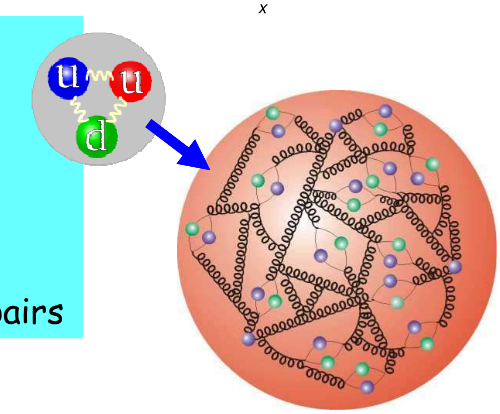
From modern DIS experiments:
Accurate parton distributions (~ F_2)

Parton distribution f(x) gives probability that a quark or gluon has a fraction x of the proton's energy.



Parton distributions tell us: there is an unlimited number of quarks and gluons in a proton at any given time. All but the three valence quarks come from quantum fluctuations.

1972: Proton = uud
2008: Proton = uud + gluons + q-antiquark pairs



The Spin Puzzle

The spin (i.e. quantized angular momentum) of a proton is ½
This spin should be "made" by the spins of the quarks inside.

"Spin crisis": All quarks inside a proton only account for 20% of the proton spin.

How can you find out? A polarized Rutherford experiment.

Currently going on: RHIC Spin

The Relativistic Heavy Ion Collider is also the world's only polarized proton collider.

The Spin Puzzle

In our modern view of the proton, there are more sources of spin:

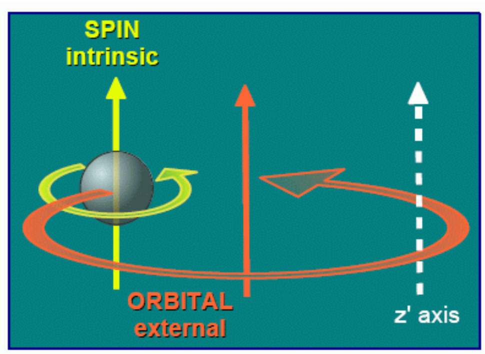
$$\langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle = \frac{1}{2}$$

quark spin

gluon spin

quark orbital angular momentum

gluon orbital angular momentum



Just measured at RHIC: $\langle S_g \rangle$ is rather small as well.

Proton spin must come from orbital angular momentum!

Ongoing research, right here at the Cyclotron!

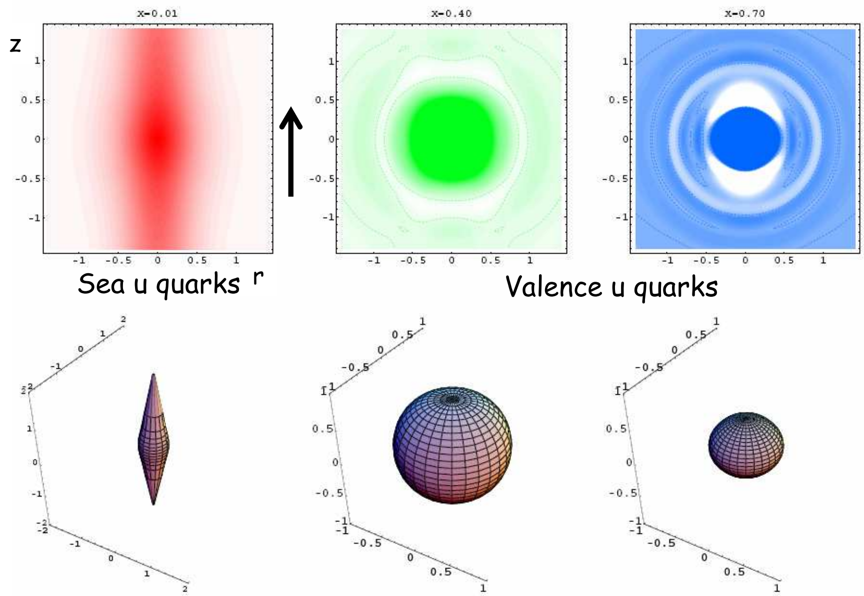
Proton Tomography

We are just starting to understand the 3-D structure of the proton.

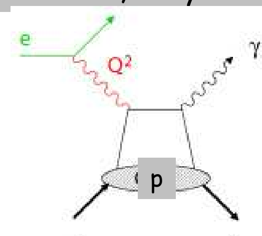
Wigner distributions of up quarks in a fast moving proton.

(computed by Ji et al.)

Proton moving this way, look from the top.



Experiment of choice: deeply-virtual Compton scattering (proton stays intact, very rare)



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.

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.

Compare the interactions:

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/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

Strong (color) spin =1

Name	Mass GeV/c^2	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/c^2	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/c^2	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/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–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)

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

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/c^2	Spin
π^+	pion	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.140	0
$\mathbf{K}^-$	kaon	$\mathbf{s}\bar{\mathbf{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.776	1
B^0	B-zero	$\mathbf{d}\bar{\mathbf{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c}\bar{\mathbf{c}}$	0	2.980	0