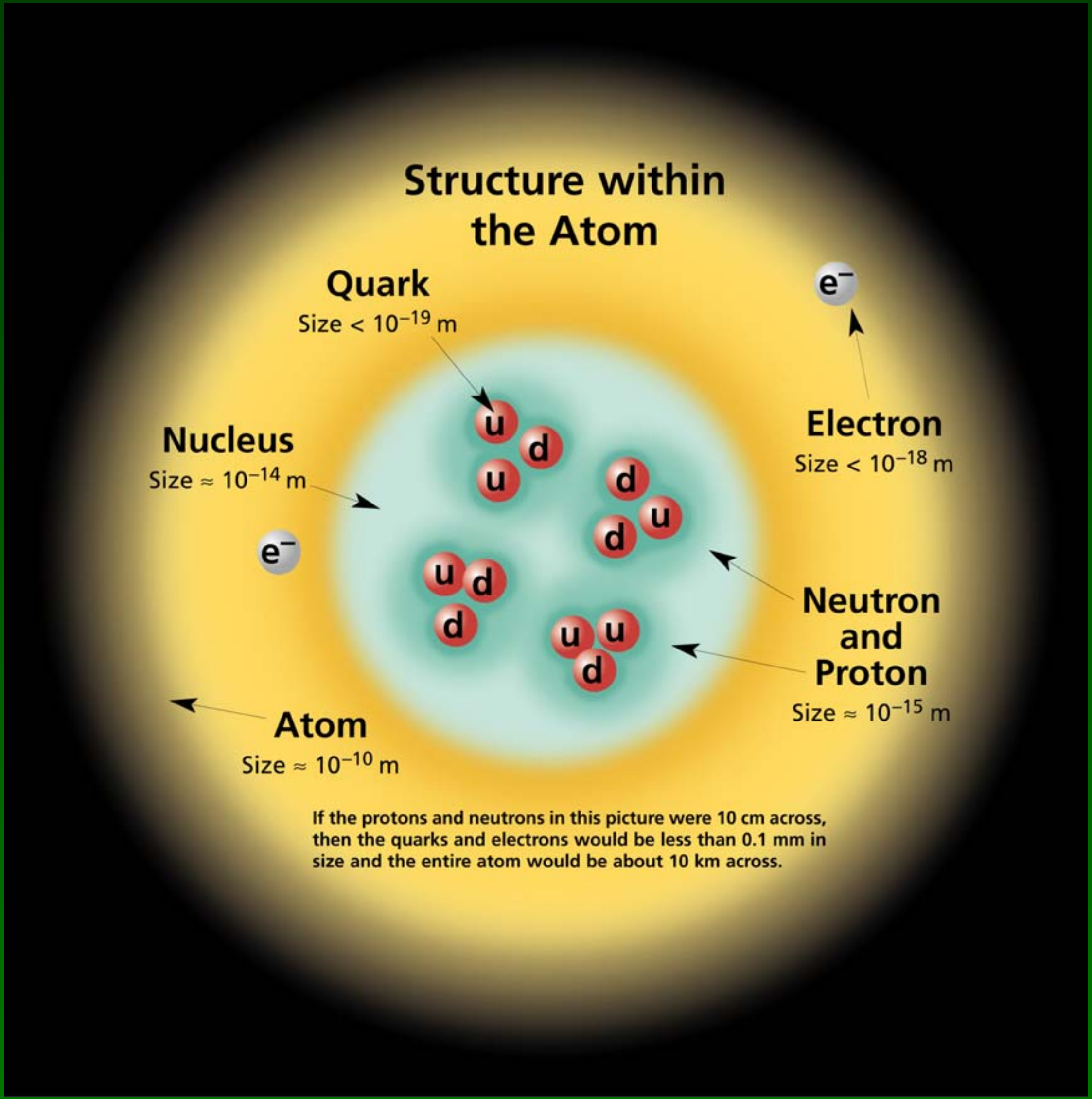
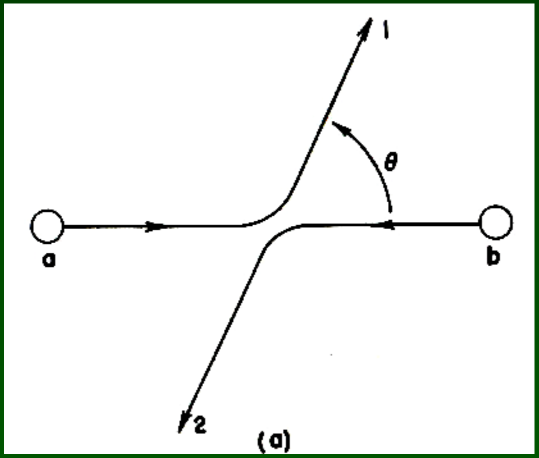
The Building Blocks of Nature



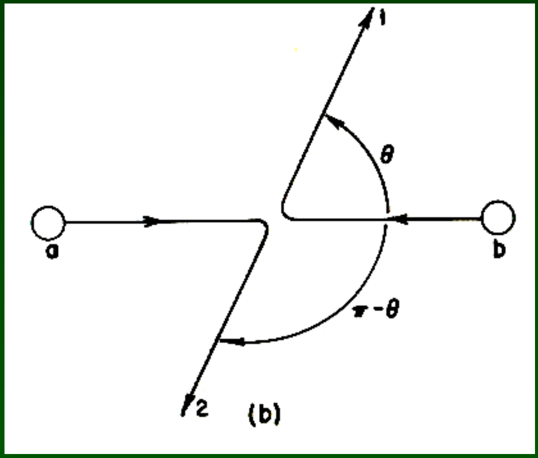
Schematic picture of constituents of an atom, & rough length scales. The size quoted for the nucleus here (10^{-14} m) is too large- a single nucleon has size 10^{-15} m, so even a U nucleus (containing 238 nucleons) is only 5 x 10^{-15} m across.

Identical Particles: BOSONS & FERMIONS



One possible path for the scattering between 2 particles with a deflection angle θ.

Another amazing result of QM comes because if we have, eg., 2 electrons, then we can't tell them apart- they are 'indistinguishable'. Suppose these 2 particles meet and interact- scattering off each other through some angle θ. Two processes can contribute, in which the deflection angle is either θ or $\pi - \theta$.



Another path contributing to the same process, assuming the particles are identical.

This means of course that both paths must be included at an equal level. Now suppose we simply EXCHANGE the particles- this would be accomplished by having $\theta = 0$. Now you might think that this means the wave-function doesn't change because the particles are indistinguishable. But this is not true- in fact we only require that

$$|\Psi(1,2)|^2 = |\Psi(2,1)|^2$$

ie., the probabilities are the same, for the 2 wave-functions. We then have 2 choices:

$\Psi(2,1) = +\Psi(1,2)$ **BOSONS**

$\Psi(2,1) = -\Psi(1,2)$ **FERMIONS**

If we add the 2 paths $G(\theta)$ & $G(\pi-\theta)$ above we must also use these signs:

$G = G(\theta) + G(\pi-\theta)$ or $G = G(\theta) - G(\pi-\theta)$

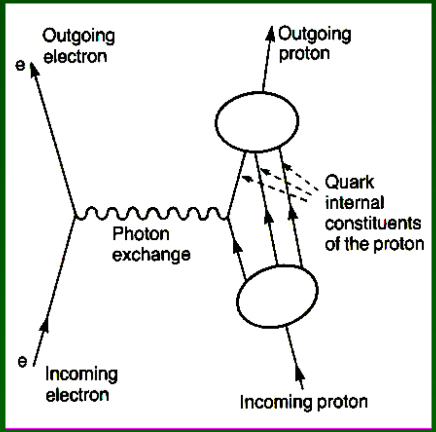
FERMIONS → MATTER…. BOSONS → FORCES

The result on the last slide is fundamental to the structure of all matter. Suppose we try & put 2 fermions in the SAME state. These could be 2 localised states, centred on positions r_1 & r_2, and then let $r_2 \rightarrow r_1$; or 2 momentum states with momenta p_1 & p_2, with $p_2 \rightarrow p_1$. These are indistinguishable particles, so that if we now swap them the equation for fermions on the last page becomes

$$\Psi(1,1) = -\Psi(1,1)$$

which is only valid if

$$\Psi(1,1) = 0$$ **(PAULI EXCLUSION PRINCIPLE)**



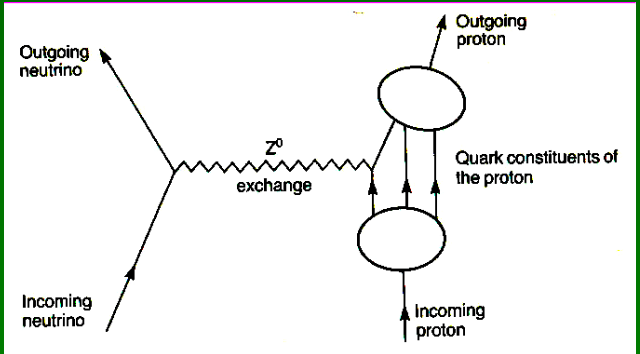
TOP: Scattering between a proton (really 3 quarks) and an electron, via photon exchange

The Pauli exclusion principle says that the amplitude and the probability for 2 fermions to be in the state is ZERO- one cannot put 2 fermions in the same state.

This result is what stops matter collapsing. Without the exclusion principle, we could put many atoms on top of each other- putting them all in the same state.

On the other hand bosons LIKE to be in the same state- we shall see later what this can lead to.

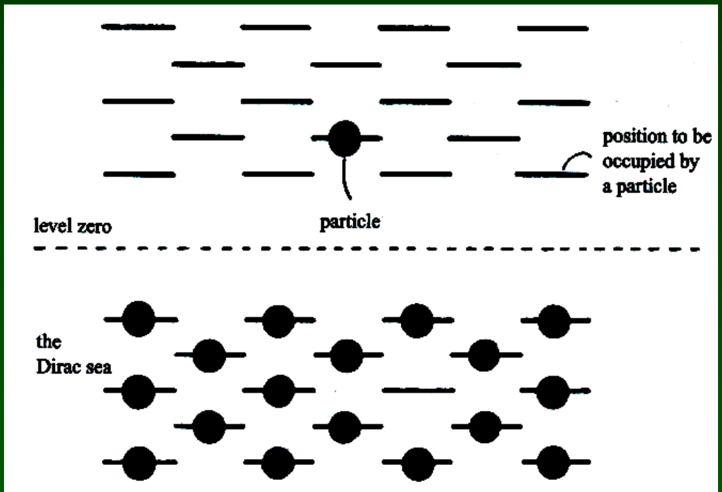
All matter is made from elementary fermions. The key role played by bosons is that they are the quanta (particles) coming from the fields that mediate FORCES in Nature.



Proton-neutrino scattering (Z^0 exchange)

PARTICLES & ANTI-PARTICLES

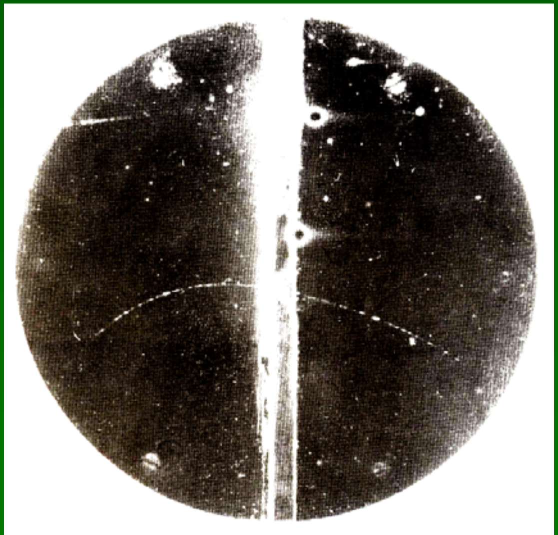
At the beginning of the 1930's, 3 basic particles were known- the -ve charged electron, called e^-, the +ve charged proton, called p^+, and the newly discovered neutron, called n. The proton & neutron live in the nucleus, and have a mass some 1850 times larger than the electron's.



The Dirac vacuum, with 1 electron excited out, leaving a positron (the empty state).

However a remarkable theoretical result fundamentally changed this picture. P.A.M. Dirac, in 1931, reconciled Einstein's special relativity with quantum mechanics, but with a startling result- all particles must have an 'anti-particle', with the same mass but opposite charge. It turns out we can imagine the 'vacuum' or ground state is actually a 'Dirac sea' of quantum states, all occupied. Exciting the system to higher levels is equivalent to kicking particles out of the Dirac sea, leaving empty states behind- these are the anti-particles! We never see the vacuum- only the excited particles and anti-particles.

If a particle and anti-particle meet, they mutually annihilate, with the excess energy emitted as bosons- in the case of an electron and anti-electron, as high-energy photons (actually gamma rays).



The discovery of the positron (C. Anderson, 1932), identified by its track.

CONSTITUENTS of MATTER

Matter is made from fermions- and it is the Pauli principle, preventing these from overlapping, that gives matter its volume and structure. We now know of many fermions, but at the most basic level yet established, they are made from QUARKS and LEPTONS.

The quarks come in 18 varieties, which are given funny names- one has 3 "colours" (red, blue, green), and then 6 flavours, shown at right. The quarks are what make up the heavy fermions.

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

Leptons spin = 1/2			
Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

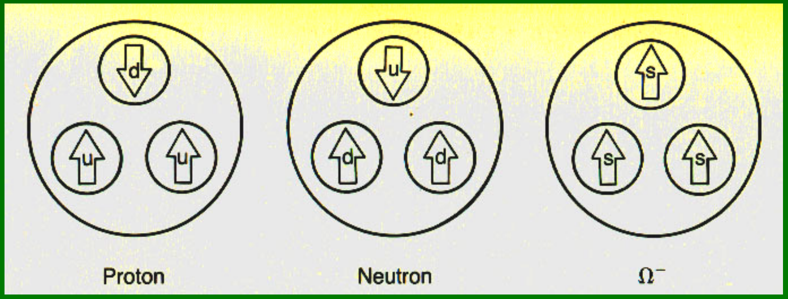
Quarks spin = 1/2			
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	−1/3
c	charm	1.3	2/3
s	strange	0.1	−1/3
t	top	175	2/3
b	bottom	4.3	−1/3

The light fermions are called leptons- also shown above. Note the leptons are ordinary spin-1/2 fermions with charge 1 or 0 (in units of electric charge), but the quarks have charges in units of 1/3 of an electron charge. The quarks can never appear freely- if we try to pull them apart, the force binding them gets even stronger (one has to create more massive particles). Physical particles like baryons are 'colourless'- made from 3 quarks, one of each colour. Many baryons can be made with different triplets of quarks.

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−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



Quark composition of p, n, and Ω^-

FUNDAMENTAL INTERACTIONS

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

The fundamental bosons are divided into 4 classes- these bosons cause interactions between fermions, and give rise to 4 fundamental forces in Nature- the strong, weak, electromagnetic, and gravitational interactions.

At very high energies things change. All interactions (with their associated particles), except the gravitational one, merge into a single complex interaction which is described by 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^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	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	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

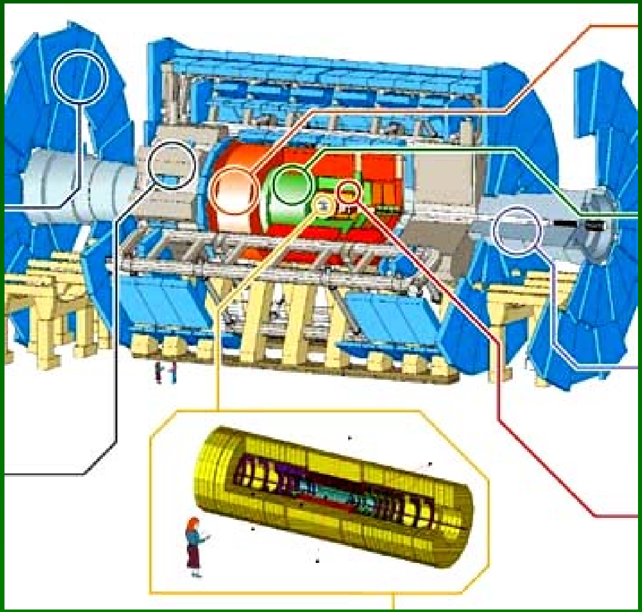
Note the strong interaction between quarks is mediated by gluons, but gluons (and mesons) are quark pairs.

EXPERIMENTS in PARTICLE PHYSICS

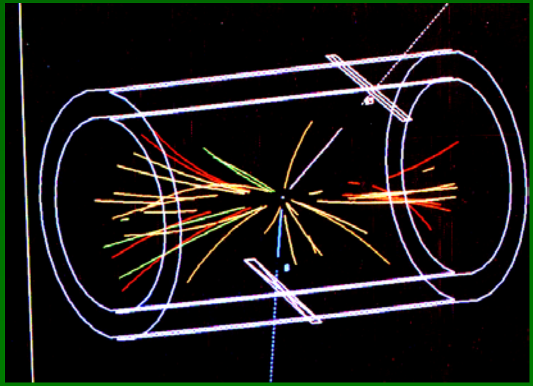
The pattern for experimental research on the building blocks of Nature was set by Rutherford, and has hardly varied since- one smashes things together at high energy, to see what comes out. The energy per particle in such experiments has now reached the TeV (10^{12} eV) level. By comparison, the ionisation energy of a H atom (the energy required to strip the electron off it) is 13.6 eV; & the energy in Rutherford scattering experiments is ~ 1 MeV (10^{6} eV). The modern experiments are huge and very expensive- they are done either in CERN (Geneva) or Fermilab (Chicago). Particles are accelerated in huge underground rings, guided by giant magnets.

ABOVE: Fermilab- aerial view

Inside the LHC ring (CERN)



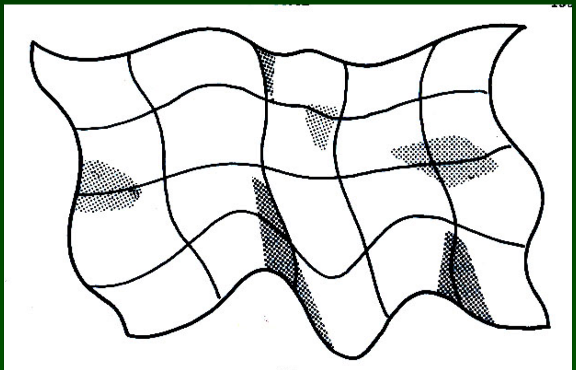
The 'ATLAS' detector (CERN)



p^{+} - p^{-} scattering (CERN)

The result of these particle smashing expts is observed by sensitive detectors. A lot of modern technology (including the world wide web), has come from this work.

Search for a unified field theory- STRING THEORY



Quantum gravity theory tries to quantize the fluctuating geometry of spacetime

Arguably the most important problem in modern physics is how to unify the standard model (ie., the strong, weak, and EM forces) with gravity. The basic problem is that (i) the fields corresponding to the first 3 forces can be 'quantized' (producing all the boson excitations we have seen), but (ii) if we try and quantize gravity, we get nonsense- interactions between quantized gravity waves ('gravitons') are infinite.

The current attempt to solve this problem is called string theory (sometimes rather stupidly called the 'TOE', for 'Theory of Everything'). This theory began over 30 years ago with attempts to control the infinities in quantum gravity.

The modern (2003) string theory has an 11- dimensional quantum 'geometry' with 7 of the dimensions 'wrapped up' very tightly (recall a geometry can be closed or 'compact'), to form 'hypertubes', only 10^{-35} m in diameter, called strings. Particle excitations (electrons, photons, quarks, etc) are wave oscillation modes of strings. 4-dimensional spacetime is the 'unwrapped' part of this.

The theory cannot be tested directly except at particle energies 10^{16} times greater than modern accelerators- this will never happen.

A string; magnified view below