Section 2.0a: the four fundamental interactions, leptons and hadrons, quarks, standard model

The four fundamental interactions and gauge bosons

What is the origin of the four fundamental forces of nature? In classical physics one explains these forces by the existence of a field. For example, two masses interact gravitationally because mass 1 will generate a gravitational field, a non-material entity that modifies the properties of the surrounding space. This field is then 'felt' by mass 2. At the classical level, gravity is described by the theory of general relativity (Einstein equations). In the weak-field limit, the gravitational force is described satisfactorily by Newton's theory.

In an analogous fashion, one can understand the electromagnetic forces between two charges: charge 1 generates an electromagnetic field which propagates through space with the speed of light, and this field causes an EM force felt by charge 2. According to Quantum Field Theory, the EM field consist of field quanta (photons). In the 1950's, Feynman, Tomonaga and Schwinger worked out the details of Quantum Electrodynamics in which the repulsive EM force between two electrons arises from virtual photon exchange described by a "Feynman diagram": a photon which is emitted by one electron (thereby causing it to "recoil") bumps into another electron (thus giving it a "kick").

Similarly, the weak nuclear force arises from an exchange of so-called intermediate vector bosons $W^\pm, Z^0$ which are very massive.

Interaction	strength	range	gauge boson	mc^2	spin	charge (e)
strong	1	10^{-15} m	8 gluons	0	1	0
EM	$\alpha = 1/137$	∞	photon	0	1	0
weak	10^{-13}	10^{-18} m	$W^\pm, Z^0$	81,93 GeV	1	$\pm 1, 0$
gravity	10^{-38}	∞	graviton	0	2	0

Table 1: Gauge bosons and their properties (July 2000 Particle Physics Booklet, LBNL and CERN)

The strong nuclear force arises from an exchange of the quanta of the "strong color field"; these quanta are called "gluons" because they provide the glue which confines the quarks inside the hadrons.

As of to date, there is not yet a satisfactory theory of quantum gravity. However, some aspects of the theory are known: the gravitational interaction between any two masses arises from an exchange of the quanta of the gravitational field called gravitons. Gravitons must have zero rest mass because the force has infinite range. From the rotational properties of the gravitational fields predicted by general relativity one deduces that gravitons carry spin 2. To detect gravitons, one must resort to the strongest gravitational fields generated in the Universe: perhaps they can be detected in gravity waves given off by black holes.

High-energy physics accelerator experiments provide unambiguous proof of the existence of the photon, the gluons, and the W, Z vector bosons. Ironically, there is no experimental evidence as yet for the field quanta of the force field that humans are most familiar with: gravity. The reason is the relative weakness of the gravitational field, see table 1.

All of the "gauge field" quanta listed in table 1 carry integer spin; according to Pauli's spin-statistic theorem, they obey boson statistics and are therefore referred to as "gauge bosons". These particles are created from the vacuum and then annihilated (absorbed) after some "lifetime" (Δt), thereby violating energy conservation by an amount ΔE, according to Heisenberg's Uncertainty Principle $\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$. To create an exchange particle of mass m requires an energy of at least

$\Delta E = mc^2$; the maximum range Δr of the exchange boson can be estimated via $\Delta r = c \cdot \Delta t$, resulting in a maximum force range given by the "reduced Compton wavelength" λ_c of the particle:

$$\Delta r \geq \frac{1}{2}\lambda_c \approx \lambda_c = \frac{\hbar c}{mc^2} \ .$$

We conclude that the range of the exchange force is inversely proportional to the mass of the exchanged "virtual" gauge boson. This explains why the weak nuclear force has such an extremely short range. A special case are the massless photons and gravitons resulting in an infinite range of the associated forces.

Leptons and hadrons

During the 1950s and '60s physicists working at several high-energy accelerators in the US and in Europe were trying to figure out what the subatomic world is made of. But instead of getting simpler, the answers got more complicated: eventually a "zoo" of several hundred "elementary" particles was discovered. Some of these particles might be viewed as excited states of existing particles while others that were created from the collision energy in the accelerator show completely new and unexpected behavior. Most of these particles have extremely short lifetimes of order 10^{-20} to 10^{-10} seconds. This "particle zoo" of more than 200 particles is highly unsatisfactory. Why should there be so many different particles? Are there any common characteristics? After a lot of trial and error, physicists found it useful to group these particles according to the type of fundamental forces they experience.

a) Leptons
Leptons are defined as particles which do NOT participate in the strong interaction, i.e. they interact only via the weak force, EM force, and gravity. Six leptons are known, which can be subdivided further into 3 generations. In table 2, the quantities L denote the lepton quantum numbers which are additive.

lepton flavor	mc^2 (MeV)	spin	L	charge (e)
electron (e)	0.511	1/2	$L_e = 1$	-1
electron neutrino (ν_e)	$< 3 \times 10^{-6}$	1/2	$L_e = 1$	0
muon (μ)	106	1/2	$L_\mu = 1$	-1
muon neutrino (ν_μ)	< 0.19	1/2	$L_\mu = 1$	0
tau (τ)	1777	1/2	$L_\tau = 1$	-1
tau neutrino (ν_τ)	< 18.2	1/2	$L_\tau = 1$	0

Table 2: Leptons and their properties (July 2000 Particle Physics Booklet, LBNL and CERN).

Experimental evidence from particle accelerators suggests that all leptons are truly elementary, i.e. they are pointlike and cannot be subdivided any further.

b) Hadrons: mesons and baryons
Hadrons are defined as particles which DO interact through the strong force. Thus, hadrons are susceptible to all four basic forces of nature. The most well-known hadrons are the nucleons (proton and neutron) and the pion. Hadrons can be further subdivided by their spin: hadrons with half-integer spins (1/2, 3/2, 5/2, ...) are called baryons, and hadrons with integer spins (0, 1, 2, ...) are referred to as mesons.

In table 3 we list the lightest non-strange mesons. These mesons are of the utmost importance for an understanding of nuclear structure physics. Virtual meson exchange is the physical mechanism that is responsible for mediating the nucleon-nucleon interaction as we will explain in detail in Section 3.

meson	mc^2 (MeV)	J^P	mean life τ or width Γ
π^0 (pion)	134.9	0^-	$\tau = 8.4 \times 10^{-17}$ s
$\pi^\pm$ (pion)	139.6	0^-	$\tau = 2.6 \times 10^{-8}$ s
η (eta)	547.3	0^-	$\Gamma = 1.18$ keV
f_0/σ (sigma)	$400 - 1200$	0^+	$\Gamma = 600 - 1000$ MeV
ρ (rho)	769.3	1^-	$\Gamma = 150.2$ MeV
ω (omega)	782.6	1^-	$\Gamma = 8.44$ MeV
η' (eta prime)	957.8	0^-	$\Gamma = 0.202$ MeV
ϕ (phi)	1019.4	1^-	$\Gamma = 4.46$ MeV

Table 3: Non-strange mesons and their properties (July 2000 Particle Physics Booklet, LBNL and CERN).

Mesons with $J^P = 0^+$ are referred to as scalar mesons, mesons with $J^P = 0^-$ are referred to as pseudo-scalar mesons, and mesons with $J^P = 1^-$ are referred to as vector mesons. The lightest-mass strange meson is the Kaon $(K^\pm, K^0)$ with $J^P = 0^-$ and $mc^2 = 493.7, 497.7$ MeV.

In table 4 we list some of the lightest baryons.

baryon	mc^2 (MeV)	J^P	mean life τ or width Γ
p (proton)	938.3	$1/2^+$	$\tau > 1.6 \times 10^{25}$ yrs
n (neutron)	939.5	$1/2^+$	$\tau = 886.7$ s
Δ (Delta)	1232	$3/2^+$	$\Gamma = 120$ MeV
Σ^+ (Sigma)	1189	$1/2^+$	$\tau = 0.802 \times 10^{-10}$ s
Σ^0 (Sigma)	1192	$1/2^+$	$\tau = 7.4 \times 10^{-20}$ s
Σ^- (Sigma)	1197	$1/2^+$	$\tau = 1.48 \times 10^{-10}$ s
Ξ^0 (Xi)	1315	$1/2^+$	$\tau = 2.90 \times 10^{-10}$ s
Ξ^- (Xi)	1321	$1/2^+$	$\tau = 1.64 \times 10^{-10}$ s
Ω^- (Omega)	1672	$3/2^+$	$\tau = 0.821 \times 10^{-10}$ s

Table 4: Low-mass baryons and their properties (July 2000 Particle Physics Booklet, LBNL and CERN).

Standard Model of Elementary Particle Physics

Ref: F. Halzen and A. D. Martin, Quarks and Leptons, Wiley (1984)

After several decades of experimental and theoretical work, elementary particle physicists have found strong evidence that all hadrons are composite particles and consist of particles referred to as "quarks". More specifically, the baryons consist of 3 bound quarks, and the mesons consist of a bound quark-antiquark pair. As far as we know, the quarks are pointlike particles with fractional electric charge; like the leptons, they are truly elementary. The strong interaction between the quarks originates from the gluon field; its field quanta are the gluons.

The "particle zoo" of hundreds of hadrons can be explained in terms of different combinations of 6 different "flavors" of quarks. There is a beautiful symmetry of nature: there are six different flavors of leptons and quarks. Like the leptons, the quarks carry spin 1/2 and can be subdivided

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further into 3 generations, as indicated in table 5:

quark flavor	mc^2 (GeV)	charge (e)
up (u)	0.005	$+2/3$
down (d)	0.01	$-1/3$
charmed (c)	1.5	$+2/3$
strange (s)	0.2	$-1/3$
top (t)	170	$+2/3$
bottom (b)	4.7	$-1/3$

Table 5: Table of quarks.

Only two flavors of quarks (the "up" quark with electric charge $+2/3e$ and the "down" quark with charge $-1/3e$) are necessary to explain the proton and neutron sub-structure: the proton consists of two up and one down quark, *uud*, and the neutron consists of one up and two down quarks, *udd*.

$p = uud$	$n = udd$		
$\Delta^{++} = uuu$	$\Delta^+ = uud$	$\Delta^0 = udd$	$\Delta^- = ddd$
$\Sigma^+ = uus$	$\Sigma^0 = uds$	$\Sigma^- = dds$	
$\Xi^0 = uss$	$\Xi^- = dss$		
$\Omega^- = sss$			
$\pi^+ = u\bar{d}$	$\pi^- = \bar{u}d$	$\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{(2)}$	
$K^+ = u\bar{s}$	$K^0 = d\bar{s}$	$K^- = s\bar{u}$	

Table 6: Quark-substructure of baryons and mesons.

The measured properties of the Ω^- baryon (it consists of 3 strange quarks in the same quantum state, all with spin-up) require the introduction of an additional quantum number called "color". Otherwise one would have to abandon the Pauli principle which works so well in atomic, molecular, and nuclear physics. Table 6 also shows that the pions and other mesons consist of various combinations quark/antiquark pairs.

Several mysteries of nature remain to be explained, in particular the origin of mass. The standard model has no mechanism that would account for the lepton and quark masses; the model assumes that the elementary particles are originally massless and that their mass arises from the coupling to the "Higgs" quantum field, a scalar field that permeates all space. The search for the Higgs boson will be one of the top priorities of the Large Hadron Collider experiments at CERN (Switzerland) scheduled to start in 2008.

The ultimate "Theory of Everything" must include a quantum theory of gravity. A promising candidate for such a theory is "superstring theory" which predicts that the quarks and leptons are not really pointlike but consist of incredibly tiny strings of size 10^{-35} m (the "Planck length"), many orders of magnitude smaller than the mean square radius of a proton (0.8×10^{-15} m).