Overview of particle physics

The big questions of particle physics are

1. What is the universe made of?
2. How is it held together?

We can start at ordinary distances and work our way down. Following that, we can also start again from ordinary distances and work up. Macroscopic stuff is made of molecules. Molecules are made of atoms. An atom has a cloud of electrons (e) surrounding a nucleus. Nuclei are made of protons (p) and neutrons (n), which are called nucleons. The electrons are held to the nucleus by electromagnetic (EM) forces—mainly just the Coulomb force. The EM force can be described by saying that the charged particles exchange the quanta of the EM field—photons (γ). The nucleons are held together in the nucleus by *strong interactions*. The associated field is called the *color field*. It is a generalization of the EM field. The quanta of the color field are called *gluons* (g). (You must be wary of the jargon in high energy physics. For example, the word color here is just a name; it has nothing to do with real colors like red and blue that we perceive directly. Also some of the jargon is imaginative, and some of it is just plain dumb. We will see why gluons have their name shortly.)

At this point, it might seem that a satisfactory universe could be built from e, p, n, γ, and g. Only the strong force would need more discussion. Things did not work out that way at all! For reasons that are not known, the universe is far richer and more interesting than that. (Perhaps it's to keep us doing physics and away from mischief that could be much worse.)

Here are some things that exist but are not obviously necessary for a nice universe:

1. Antiparticles: For example, the antiparticle of the electron is the positron e^+. It is just like the electron except for having the opposite charge. Similarly, the antiproton $\bar{p}$ and the antineutron $\bar{n}$ exist. Since the neutron has no charge, how do the neutron and the antineutron differ? The neutron (as well as the proton) has another kind of charge called *baryon number* B, which is not zero. The n has B=1, and the $\bar{n}$ has =-1. For the electron, B=0. Some particles such as the photon are truly neutral and are their own antiparticle. Antiparticles seem to be required by relativity and locality/causality. There is also a nice particle-antiparticle symmetry called TCP for time reversal, charge conjugation, and parity. Since these things are pleasing to us, we can accept antiparticles without too much worry. But then we must ask why there are so many particles around and so few antiparticles. There is a definite asymmetry in the quantity of matter vs. antimatter in the universe. There is much more hydrogen with ep than antihydrogen with $e^+\bar{p}$. There are some interesting ideas on this but no definite answer yet. This general situation where there is a symmetric underlying law but asymmetric phenomena is a recurring theme. In certain other contexts, it is called *spontaneous symmetry breaking*.
2. β-decay of the neutron: A neutron that is not bound in a nucleus is unstable and decays with a lifetime of 886 sec. via $n \rightarrow pe\bar{\nu}_e$. Associated with this, there is a new particle, the neutrino (In this case, it's the electron's antineutrino.), and a new force, the weak interaction.
3. Quarks: The strong interaction is not a simple force between nucleons. The nucleons are not fundamental. Each nucleon is made of three *quarks*. So far as we know today, the quarks are fundamental spin-1/2 fermions. Two kinds of quarks are needed to make ordinary matter. The label for the different kinds is called *flavor*. Of course, this has nothing to do with ordinary flavor. The two flavors are up u and down d. (I told you that some of the jargon is dumb.) A proton is uud, and a neutron is udd. It is the quarks that have the color charge of the color field. Each flavor of quark comes in three colors: red,

blue, and green. The theory of the colored quarks and the color field is called quantum chromodynamics (QCD). It is a generalization of the Maxwell equations, which are the basic equations of electrodynamics. This color force acts to glue the three quarks together to make the nucleon. That is why the quanta of the color field are called gluons.

Now for a little bit on units. Every specialty has its own convenient units. In high energy physics, we tend to measure many things in energy units. The convenient energy units are MeV, GeV, or TeV—millions, billions, or trillions of electron volts. One electron volt is the energy that an electron gains by falling through an electric potential drop of one volt = 1.60×10^{-19}J. Now introduce the speed of light c. Notice that MeV/c has momentum units and MeV/c^2 has mass units. The next step is to choose length and time units so that the speed of light c=1. Then energy, momentum, and mass are all measured in energy units. (This brings to mind the famous Einstein relation $E=mc^2$.) To get lengths into the picture, recall another famous relation (from de Broglie this time) $p=h/\lambda=\hbar k$. In this, p is the momentum, h is Planck's constant, $k=2\pi/\lambda$ is the wave number, and $\hbar=h/2\pi$. The units of $\hbar$ are momentum length. Now choose length units so that $\hbar=1$. That leaves length with units of inverse momentum or equivalently inverse energy. This is all very weird but very convenient once you get used to it. Thus, energy, momentum, and mass are all in MeV and length is in 1/MeV. To get back to standard units, you need to know two numbers $c=3 \times 10^8$m/s and $\hbar c=197$MeV f. (f=fermi=fm=10^{-15}m.) For example, for mass, 1 GeV=1 GeV/c^2=1.78×10^{-27}kg, and for length, 1/GeV=$\hbar c$/GeV=0.197×10^{-15}m. The proton and neutron masses are both close to 1 GeV. The proton mass is 938.3MeV, and the neutron is 1.3MeV heavier at 939.6MeV.

Let's return to the big questions. As we understand it today, the ordinary stuff of the universe is made of four matter particles. There are the electron e and its neutrino ν_e, which are called *leptons*, and the two quarks u and d. For each quark, there are the three colors, and for each particle, there is also its antiparticle so we are really talking about (1+1+3+3)x2=16 particles.

Particle	Charge	Mass
electron neutrino ν_e	0	< 3eV
electron e	-1	0.511MeV
up quark u	2/3	"4.3MeV"
down quark d	-1/3	"7.5MeV"

This is called the first *family*.

The universe is held together by four forces. For each of these forces, there is an associated field and an associated quantum for that field. The field quantum appears as a particle.

Force	Quantum	Charge	Spin	Mass
Gravity	graviton	0	2	0
EM	photon γ	0	1	0
Weak	W^+, W^-, Z^0	+1, -1, 0	1	80.4, 80.4, 91.2GeV
Strong	gluon g	0	1	" 0 "

I will explain later why some of the masses are in quotes.

And now for the deep mystery: In some extravagant, impulse shopping, Nature bought two more families of quarks and leptons. These have the same structure as the first family. The difference is that the masses are larger.

Particle	Charge	Mass
muon neutrino ν_μ	0	< 0.19MeV
muon μ	-1	105.7MeV
charm quark c	2/3	"1200MeV"
strange quark s	-1/3	"150MeV"

Particle	Charge	Mass
tau neutrino ν_τ	0	< 18.2MeV
tau τ	-1	1777MeV
top quark t	2/3	"174GeV"
bottom quark b	-1/3	"4.7GeV"

No one understands the reason for more than one family or the values of the masses. These are active research areas.

Neutrino masses: There is now convincing evidence that neutrinos are not massless, but the masses may be as small as about 0.05 eV.

Since the six quarks and their antiparticles can be combined into bound states in many ways, many particles in addition to the p and n are possible. Hundreds of these have been observed. One of the great accomplishments of the quark model has been to give a unified description of these many states.

Here is some more jargon: These are names for classes of particles.

1. *Fermions* are particles for which you are allowed to put only one of them in a given state. This is called Fermi-Dirac statistics. All the leptons and quarks are fermions.
2. *Bosons* are particles for which you are allowed to put any number in the same state. In fact, putting more in the same state is favored. This is called Bose-Einstein statistics. The photon, the gluon, and the other quanta of the force fields are bosons.
3. *Leptons* are the fermions that do not have strong interactions. These are the e, μ, τ, and their neutrinos.
4. *Hadrons* are the strongly interacting particles.
   a) *Mesons* are the hadrons that are also bosons, e.g. π, ρ, ω and K.
   b) *Baryons* are the hadrons that are also fermions, e.g. p, n, Δ, Λ, and Σ.

Even though there are just four interactions, particle physicists dream of and work on a more unified description. There has been no great progress so far. However, some important work has been done. The Glashow-Weinberg-Salam theory of the electroweak interaction sort of unifies the EM and weak interactions in a way that is not particularly pretty (except that it accounts for a huge body of experimental results). The electroweak theory combined with QCD is referred to as the *Standard Model*. It contains one more fundamental particle that was not listed above. It is called the *Higgs boson*. It is closely related to the W and Z and to the large masses that they have. It has not yet been observed. One of the biggest activities in high energy physics these days is looking for the Higgs. There is no experimental result that forces us to look beyond this theory.

Nevertheless, considerable effort is devoted to looking for more unified theories. Those that unify QCD and the electroweak theories are called *grand unified theories (GUTs)*. The simplest of these is based on the gauge group SU(5), which is big enough to contain the SU(3)xSU(2)xU(1) of the standard model. The SU(5) model has many nice features. It is unique in making predictions that are difficult to wiggle out of. Unfortunately, one of these is wrong. Most GUTs, including SU(5), predict an unstable proton. SU(5) gives an actual number for the decay rate, which would have been seen by now in the current ambitious experiments. It has not been seen. However, there is new hope for the SU(5) GUT in a supersymmetric version. With the addition of supersymmetry, there are new particles, which alter the way the running couplings run. The interactions unify at a higher energy scale, and the proton lifetime increases enough to be out of range of current experiments.

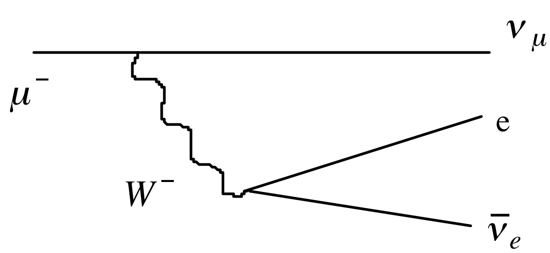
Even more ambitious theories try to get gravity into the picture. Recent attempts along this line are characterized by a new symmetry called *supersymmetry*. This symmetry transforms fermions into bosons and visa-versa. Early versions were called supergravity models. Later versions are in the context of string theory and are called superstring models. In string theory, the fundamental objects are not particles or fields; they are strings with extent in one dimension.

Decays and lifetimes

The truly stable (not yet observed to decay) particles are γ, ν's, e, and p. All others decay by weak, EM, or strong interactions. Those that are truly stable and those that decay by weak or EM interactions have much longer lifetimes than they would if they could decay strongly. They are called stable particles. The ΔEΔt uncertainty relation tells us that lifetimes and widths are inversely related τΓ~1.

Weak decays

Typical is $\mu \to \nu_\mu e \bar{\nu}_e$ with a mean life $\tau \cong 2.2 \times 10^{-6}$ sec. The picture for this is



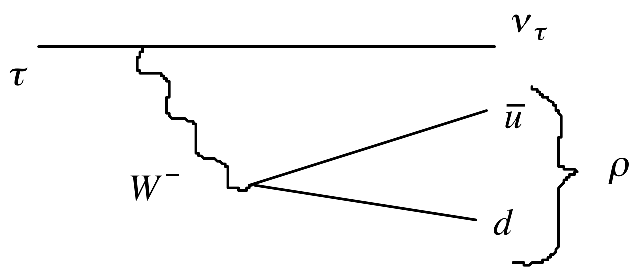
For the τ, $\tau = 2.9 \times 10^{-13}$ sec., and there are a number of possibilities

$\tau \rightarrow \nu_\tau \mu \bar{\nu}_\mu$ 17%

$\tau \rightarrow \nu_\tau e \bar{\nu}_e$ 18%

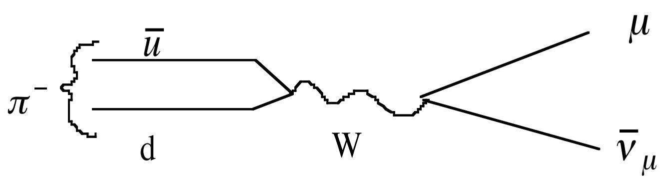
$\tau \rightarrow \nu_\tau \rho$ 25%

and others. Notice that the τ *lepton* can decay into the ρ *hadron*. The picture is

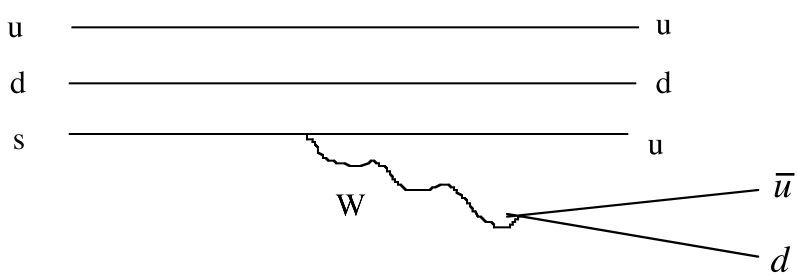


Some hadrons have weak decays only. Examples:

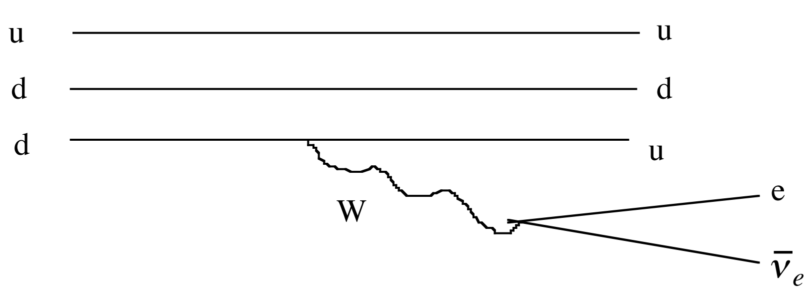
$\pi^- \rightarrow \mu \bar{\nu}_\mu \qquad \tau = 2.6 \times 10^{-8}\ \text{sec}.$



$\Lambda^0 \rightarrow p \pi^- \qquad \tau = 2.6 \times 10^{-10}\ \text{sec}.$



The classic weak decay is neutron beta decay.



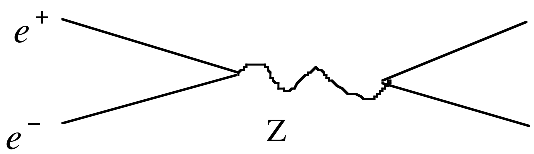
$\tau = 886\ \text{sec}.$

The W and Z bosons of the weak interaction can be produced, and their properties can be observed. Since the W and Z are so heavy, there is a large phase space and many available final states. The lifetimes are short, and the widths are large.

$$W^- \to e\bar{\nu}_e,\ \mu\bar{\nu}_\mu,\ d\bar{u},\ldots \qquad \Gamma_W = 2.1 GeV$$

$$Z \to e^+e^-,\ \mu^+\mu^-,\ u\bar{u},\ldots \qquad \Gamma_Z = 2.4952 \pm 0.0026 GeV$$

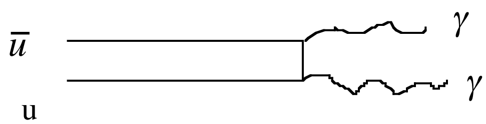
Note that $Z \to \nu\bar{\nu}$ contributes to the Z width for each neutrino with $m_\nu < m_Z / 2$. In the three known families, even though the quarks and charged leptons get heavier and heavier, the neutrinos are all light. A precise measurement of Γ_Z tells the number of light neutrinos. If there were more families with quarks and charged leptons too heavy to have been discovered, but with light neutrinos, like the known families, Γ_Z would reveal them. The experiments on the Z width at SLAC/SLC and CERN/LEP observe the process



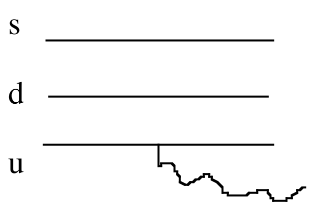
on resonance and show that the number of light neutrinos is three. Thus if there is a fourth family, it must have heavy neutrinos.

EM decays

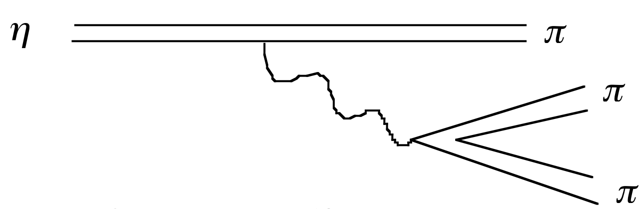
Here the rates are generally faster (other things being equal). Some examples:



$\pi^0 \to \gamma\gamma \qquad \tau = 0.87 \times 10^{-16}$ sec.

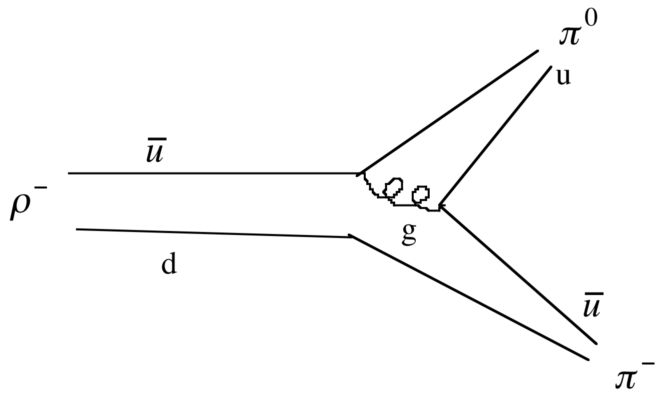


$\Sigma^0 \to \Lambda^0\gamma \qquad \tau = 7.4 \times 10^{-20}$ sec.



$\eta \to 3\pi^0 \qquad \tau \approx 10^{-18}$ sec. Note that there is no final state photon in this case!

Strong decays
These are faster still. Examples:



$\rho \to \pi\pi \qquad \Gamma = 153 MeV$.
A strong baryon decay is $\Delta^{++} \to p\pi^+$ with $\Gamma = 110 MeV$.

If a particle can decay strongly, it will and will be gone before any possible EM or weak decays have a significant chance to work. If no strong decays are possible because the particle does not have strong interactions or because the only available final states have a different I-spin, then an EM decay may happen. If that is not possible, then finally the weak decay may be seen. Strong decays conserve "everything". EM decays violate I-spin. Weak decays can violate I-spin, all other flavor quantum numbers (strangeness, charm,...), C, CP, and probably T but not CPT. Some things like EM charge and energy momentum seem to be conserved for good reason. Some others like baryon number and lepton number seem to be conserved but for no apparent reason.

Cross sections

These follow a similar pattern. Strong interaction cross sections are large.
For $\pi^+ p, \quad \sigma_T \approx 30 mb \left(1b = 1 barn = 10^{-24} cm^2\right)$.
EM cross sections are smaller. For $\gamma p, \ \sigma_T \approx 100 \mu b$.
Weak cross sections are very small. For $\nu p, \ \sigma_T \approx 10^{-11} mb$ at $E_\nu = 1 GeV$.

Probing short distances requires high energy and large, expensive accelerators. The ultimate high energy experiment has already been done. It was the big bang. Our universe is the final state from that event. Cosmology and general relativity tell us that the temperature T of the universe is related to the time t after the big bang by $T \propto t^{-1/2}$ at early times. So at sufficiently early times, particle energies were arbitrarily large. For example, at $t = 10^{-12}$ sec, $kT \cong 1 TeV$. There is now a lot of interesting work combining particle physics and astrophysics.

Dark matter and dark energy

Return now to ordinary distance scales and look outward to larger astrophysical and cosmological scales much larger that our ordinary experience. From relatively recent observations, several shocking conclusions have been drawn:

1) Most of the ordinary matter (protons, neutrons, electrons, etc.) in the universe is not in stars and is hidden from us. Altogether, the ordinary matter makes up only 5% or so of the energy in the universe. The part that we see in stars is only a small fraction of that.

2) Most of the matter in the universe is not ordinary, and we do not know what it is. (By matter, we mean stuff that clumps up due to gravitation.) However, there are some plausible candidates among the postulated but undiscovered particles. A leading contender is a neutral particle in a supersymmetric theory. The non-ordinary dark matter is about 25%.

3) Most of the energy in the universe (about 70%) is not matter but some kind of stuff that is spread uniformly over space like a vacuum expectation value of a quantum field or a cosmological constant. To fit the observations of an accelerating expansion of the universe, it needs to have negative pressure.

Thus we now know that we know far less than we though we did only a few years ago about the answer to the question: What is the universe made of? At the moment, we can account for less than 1% of it. There is plenty of work to be done!