Introduction to Particle Physics

Particle physics is the current frontier of the reductionist approach to understanding matter and its interactions. The subject is dedicated to understanding what the most basic building blocks of matter are and how they interact.

The long term goal is a "theory of everything" which mathematically describes these building blocks under all conditions. We might hope on aesthetic grounds for some huge unification of physics leaving a theory of just one sort of particle and one sort of interaction. Such an idea is strongly hinted at by the progress of physics to date where a vast array of phenomena have been distilled down to a relatively few laws - eg all of the phenomena of electricity and magnetism now reside in a single theory. We can not though, of course, demand this of nature if she doesn't want to cooperate! One could imagine a "Russian doll" scenario where matter continues to be found to have smaller and smaller constituents as we look on smaller and smaller scales ad infinitum. Philosophically we may worry even in the case of a final theory why the particular fundamental particles and laws are the ones nature chooses. The answer to such a question seems beyond the power of science even in principle. Nevertheless the goal of a complete mathematical description of the building blocks of nature is enough to be getting on with!

We should also note that a reductionist "theory of everything" does not mean that we understand everything. Many interesting bits of science are about how novel physical behaviour emerges from the interactions of many of the fundamental constituents. Examples are superconductors, stars, life, consciousness etc.

1 The Building Blocks of Matter

Let us summarize the content of our current understanding of matter. Everyday matter is made of atoms whose properties are determined by the charge of their nuclei and hence the number of electrons electromagnetically bound to them.

The nuclei are made of positively charged protons and neutral neutrons. It turns out that these nucleons are in turn made up of fundamental particles called quarks. A proton contains two up quarks and a down, a neutron two downs and an up. These quarks are bound together by the strong nuclear force which in fact "confines" them into the nucleons - we can never free a quark on its own. The Van der Waals type forces of this interaction bind the nucleons together into the nucleus.

Finally we observe radio-active β-decay in which

$$n \to p\ e^-\ \bar{\nu}_e, \quad \text{or} \quad d \to u e^- \bar{\nu}_e \tag{1}$$

from which Pauli deduced the existence of the fourth constituent, the neutrino. This decay is the result of the weak force.

To summarize:

type	particle	electric charge	strong ints	weak ints	mass
form hadrons	u	+2/3	yes	yes	4 MeV/c^2
	d	-1/3	yes	yes	6 MeV/c^2
leptons	e	-1	no	yes	0.5 MeV/c^2
	ν_e	0	no	yes	tiny

The electric charges are multiples of $1.6 \times 10^{-19}C$ and $1eV = 1.6 \times 10^{-19}J$.

In addition to each of these particles cosmic ray experiments showed there to be anti-particle copies of each of these particles that are identical in all respects but have the opposite charges. These are written as $\bar{u}, \bar{d}, e^+, \bar{\nu}_e$.

In more modern times particle physics is performed by colliding electron positron pairs and converting their total energy into the rest mass of new particles. These experiments have revealed that there are two additional exact copies of all the above particles except with larger masses. The three copies of the particles are called the three families. In normal life the heavy families decay into the lighter families by the weak force.

The second family consists of

charm,c	strange, s	muon, μ	ν_μ
1.4 GeV/c^2	150 MeV/c^2	105 MeV/c^2	tiny

The third family consists of

top,t	bottom, b	tau, τ	ν_τ
175 GeV/c^2	4.5 GeV/c^2	1.8 GeV/c^2	tiny

2 The Four Forces

Lets us briefly introduce the properties of the four forces of nature.

2.1 Electromagnetism

Electromagnetic forces can be described by electric and magnetic fields $\vec{E}$ and $\vec{B}$ or the scalar and vector potentials ϕ and $\vec{A}$. In a relativistic context the potentials combine to be the components of the four vector potential A^μ. Wave solutions of Maxwell's eqns for these fields describe light.

Quantum mechanically the energy in these fields is quantized coming in lumps of magnitude $E = h\nu$. We treat a field with just one individual lump of energy as a a particle called the photon.

The minimal interaction between say two electrons is by the exchange of one quanta of energy. One can not see light streaming between the particles though - the exchanged photons are in fact "virtual particles" created out of energy borrowed using the uncertainty principle

$$\Delta E \Delta t \sim \hbar \tag{2}$$

Since the rest mass of the photon is zero a virtual photon can be created with sufficiently small energy that it can survive for an arbitrarily long time which is why the electromagnetic force is a long range force. Note that since these virtual photon's energy and momentum are the result of the uncertainty principle the usual classical ideas of how momentum is exchanged do not apply. It is possible for these virtual particles to mediate attraction!

2.2 Strong Nuclear Force

The strong nuclear force acts on quarks and binds them together into hadrons. The theory is similar in structure to that of electromagnetism although there are three sorts of charges rather than just one. There are again "chromo"-electric and magnetic fields whose massless quanta mediate the force. The presence of three charges though results in the force behaving very differently and in particular explains why it is strong enough to confine quarks and the chromodynamic fields. We will learn more about this force later in the course.

2.3 Weak Nuclear Force

The weak force has many peculiar characteristics such as its ability to change the flavour of particles. We will learn how to turn this into a theory like those describing electromagnetism and the strong force. There are again force carrrying particles (W and Z bosons) but in this case they are very massive ($M_W = 80GeV/c^2$). Using the uncertainty principle we can see that there is a maximum time such a boson can last for as a virtual particle. Assuming they travel no faster than the speed of light there is therefore a maximum range for the force. This is why the weak force is weak. We will need to postulate the existence of a particle called the higgs boson to explain the W and Z masses. Much of current particle physics research and experiment is the attempt to discover this particle.

2.4 Gravity

The ratio of the force strengths in normal life is roughly

$$\begin{array}{c} \text{strong} : \text{EM} : \text{weak} : \text{gravity} \\ 1 : 10^{-2} : 10^{-7} : 10^{-38} \end{array}$$

Not surprisingly therefore we have never observed the gravitational force between two electrons (we only know about the force between bodies made of many millions of atoms). In a sense therefore gravity is not part of particle physics. This does not stop people trying to build a sensible quantum theory of gravity although only with limited success so far. Gravity is not a theory like the other force theories and so we have less guidance as to what the final theory should look like.

2.5 The Tasks to Come

The purpose of this course is to teach you about the current understanding of these particles and their interactions in collider experiments. We will have guest lectures by an experimentalist from the Rutherford Lab near Oxford on how one builds a collider and detects the particles it produces. The rest of the course will be about the theory of these interactions. We will need to master

- Relativistic quantum mechanics - we will learn about the origins of anti-particles and spin
- Quantum Electrodynamics
- Quantum Chromodynamics
- Standard Model of Weak Interactions
- Ideas beyond the Standard Model