E212: Properties of Elementary Particles

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March 30, 2018

Abstract goes here

1 Introduction

Introduction text

2 Theory

Our current best understanding of particle physics is the Standard Model of particle physics (SM). This model describes our discoveries of fundamental particles and their interactions with each other, mediated by fundamental forces. It furthermore describes the way these particles and forces combine to form atoms, from which many of the physical phenomena we encounter in everyday life can be explained. The main shortcoming of the SM however, is its inability to be united with gravity. That said, due to the relative weakness of gravity in comparison to the other fundamental forces, it rarely has an effect in particle physics and thus is mainly ignored.

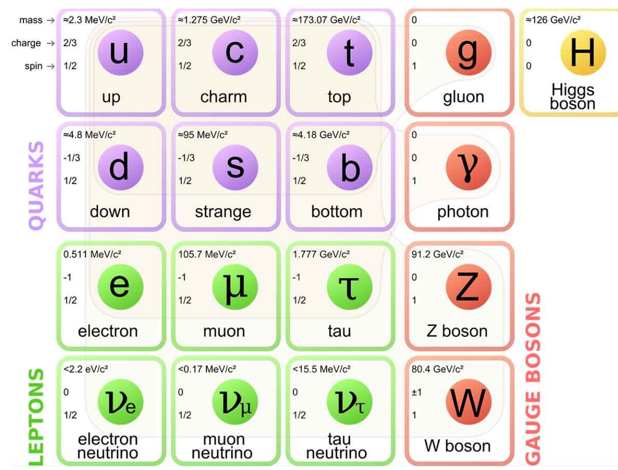

Figure 1: Illustration of the elementary particles in the SM. Quarks are in purple and Leptons in green, arranged into generation columns from left to right. The gauge bosons are in red, with the scalar Higgs boson in yellow.[5]

2.1 The Standard Model

Figure 1 give a summary of the particles in the SM with their most basic properties. Furthermore, there also exists anti-particles of many of these particles. An anti-particle, such as a positron, is identical to its particle (electron) apart from having the opposite electric charge. A neutral particle is often its own anti-particle such as the Z boson, though neutrinos have anti-particles which are merely distinct by having opposing spin projections. All matter particles and the W bosons have anti-particles while the rest are their own anti-particles. Quarks and leptons make up all the matter particles that have been discovered. These are given in three generations of particles, shown with the columns from left to right in the figure. Matter that is encountered everyday is largely structured from the first generation, namely the electron, electron neutrino, up quark, and down quark. For example, atoms are made up of electrons, protons, and neutrons, the latter two being composed of up and down quarks. The second and third generations are composed of particles which are otherwise exactly identical to their first generation counterpart apart from being heavier, the third generation being the heaviest of them all. This is only known to be true for the charged leptons (electron, muon, and tau) and quarks however. Though the neutrinos are known not to be massless, they have very small masses which have not been accurately measured. It is unknown which is the most massive and which the least.[1] Figure 2 illustrates the relative masses of the matter particles. The main reason why the second and third generation of particles are largely not existent in everyday phenomena is due to the requirement that higher energies are needed to produce these heavier particles. Furthermore, these heavier particles have shorter lifetimes due to their favourable decay into lighter particles, such as those in the first generation, due to the fundamental tendency of physical systems to higher kinetic energy states. Particle physics experiments need to be performed at increasingly higher energies in order to produce more massive particles that we do not readily observe. This is illustrated in Figure 3. It should

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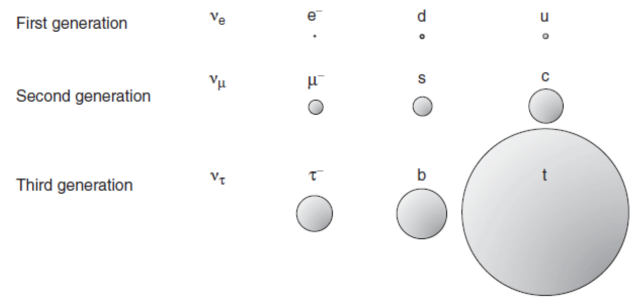

Figure 2: Illustration of the relative masses of the matter particles in their respective generations. The neutrinos are left blank to show that their masses are extremely small in comparison the other particles.[1]

be noted that though neutrinos are not seen, trillions of solar neutrinos pass through your body each second, oscillating between their three different flavours.[1] They are extremely difficult to detect due to the fact that they have a small mass and no electric charge.

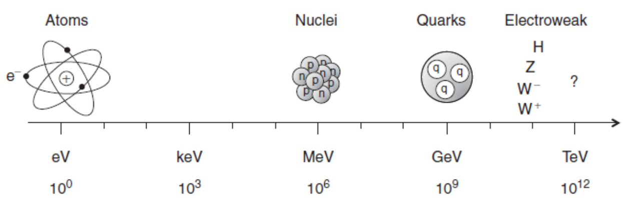

Figure 3: Illustration of the energies required to probe different structures and particles.[1]

Figure 1 also shows the fundamental forces in the SM which are all mediated via the exchange of a gauge boson. The most familiar of these is the photon γ which mediates the electromagnetic force, responsible for electricity, magnetism, and light. The photon interacts with all particles that have an electric charge and thus with all matter particles in the SM apart from the neutrinos. It also interacts with the W bosons as they are electrically charged. The gluon gauge bosons mediate the strong force, thus called as it is the strongest force and binds nuclei and hadrons together, explained in Section **??**. The gluons interacts only with particles which have a so-called "colour" charge, another property of particles similar to electric charge. Only quarks have a colour charge and the eight differently coloured gluons. Next, the oppositely charged $W^{\pm}$ and Z bosons mediate the weak interaction, the weakest force apart from gravity. This force is responsible for radioactive decay and interacts with all matter particles in the SM. Finally, the Higgs boson is the most recently discovered particle which gives mass to all the matter particles in the SM by interacting with them.

2.2 Hadrons and the Strong Force

Though quarks are elementary in the SM, they cannot be observed as free particles. This is because quantum chromodynamics (QCD) of the SM, the theory of the strong force, states that colour is confined such that systems with a colour charge cannot propagate freely. Instead, only colourless composite particles can be observed, termed "colour confinement". As a result, quarks form composite particles called hadrons which are bound by gluons. Hadrons generally form baryons, composed of three quarks, and mesons, composed of one quark and one anti-quark. The reason for the these two types is a result of there being three colours, red, blue, and green, and three anti-colours, anti-red, anti-blue, and anti-green. Colourlessness is achieved by combining all three colours (or anti-colours) in a baryon, or a colour and its anti-colour in a meson, as shown in Figure 4. Protons and neutrons are examples of baryons, composed of two up quarks and one down quark (written as uud), and two down quarks and one up quark (udd), respectively. Furthermore, exotic hadrons, which achieve

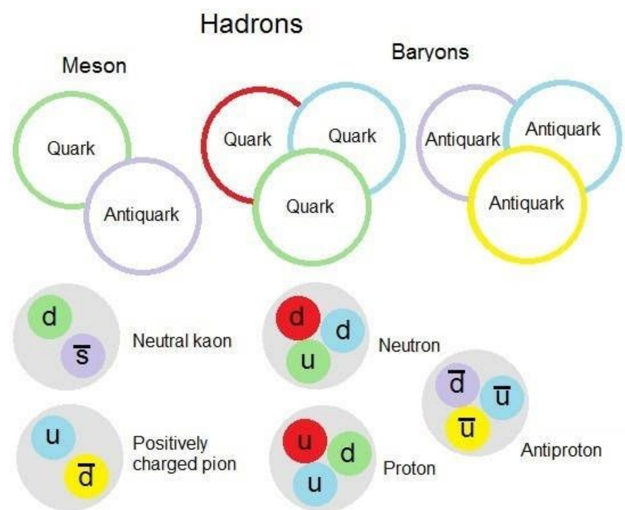

Figure 4: Colour confinement resulting in baryons and mesons, given with some examples.[6]

colour confinement with more quarks, have been hypothesised and observed, though without explicit confirmation that the observations were indeed bound exotic hadrons. Examples include the tetraquark with two quarks and two respective anti-quarks, and the pentaquark with four quarks and an anti-quark. Exotic hadrons are rare however, due to the tendency of quarks to form and decay quickly into mesons and baryons.

2.3 Multiplets

The quark model of QCD just explained was originally proposed from a group theoretic perspective by Murray Gell-Mann among others in the 1960s. This method has proven to be extremely accurate at predicting particles and their properties, explaining all the hadrons that have been observed. It predicts all the possibilities of obtaining colourless composite particles from the quarks in the SM, as well as the colours and the anti-colours. Hadrons are often grouped into so called "multiplets" in this framework by their composite particles. Figure 5 shows one such multiplet of mesons formed from up, down, and strange quarks, as well as their anti-quarks. Noteworthy

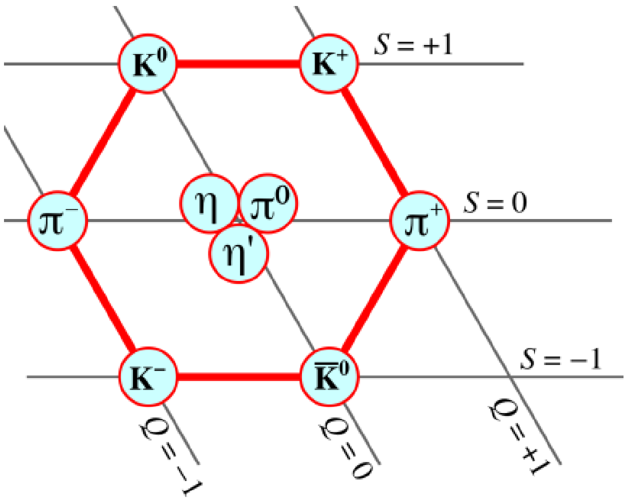

Figure 5: The light pseudoscalar meson nonet, plotted against strangeness and electric charge axes.[7] It is called the light nonet as it is composed of the lightest quarks, resulting in the lightest meson multiplet.

is the strangeness quantum number, shown in the figure, defined as $S = n_{\bar{s}} - n_s$, where $n_{\bar{s}}$ and n_s are the number of strange anti-quarks and quarks in the hadron, respectively.[1] Strangeness has been observed to be conserved in strong and electromagnetic interactions, but not in weak interactions. The pions are of particular importance of this experiment. The $\pi^\pm$ and π^0 have masses[8]

$$
\begin{aligned}
m_{\pi^\pm} &= (139.57018 \pm 0.00035)\ \text{MeV}, \\
m_{\pi^0} &= (134.9766 \pm 0.0006)\ \text{MeV},
\end{aligned}
$$

and mean lifetimes

$$
\begin{aligned}
\tau_{\pi^\pm} &= (2.6033 \pm 0.0005) \times 10^{-8}\ \text{s}, \\
\tau_{\pi^0} &= (8.52 \pm 0.18) \times 10^{-8}\ \text{s}.
\end{aligned}
$$

Their main decay modes are

$$
\begin{aligned}
\pi^+ &\to \mu^+ \nu_\mu \to (e^+ \nu_e \overline{\nu}_\mu)\, \nu_\mu, \\
\pi^- &\to \mu^- \overline{\nu}_\mu \to (e^- \nu_\mu \overline{\nu}_e)\, \overline{\nu}_\mu, \\
\pi^0 &\to 2\gamma,
\end{aligned}
$$

where the resulting decays of the muons are given in brackets. The branching ratios of these decays are 99.99% for the charged pions and 98.82% for the neutral pion, showing that these particular decays largely dominate pion decays.[8] In this experiment however, the π^- has a much higher probability of participating in a scattering process $\pi^- \to n\pi^0$ due to the presence of and thus any so-called $\pi\mu e$ decay observed will most likely be a π^+ decay. It should be noted that there exists other meson multiplets apart from the one shown in Figure 5, composed of other quarks.

Figures 6 and 7 show two examples of baryon multiplets that are relevant in this paper. Both the octet and

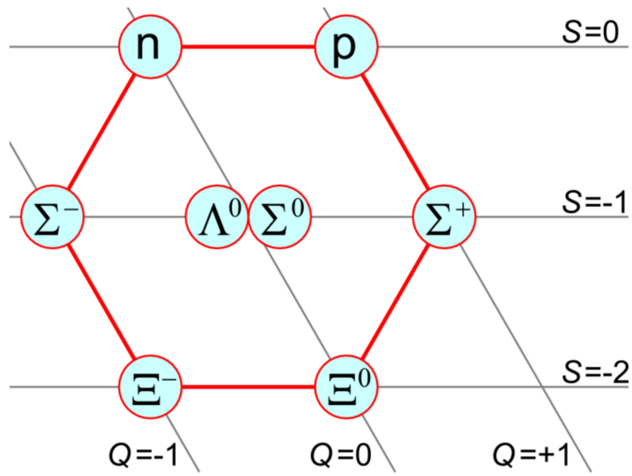

Figure 6: The light baryon octet.[9] Note the similarity to the mesons nonet, yet composed of one less particle and having no positive strangeness particles as none are composed of anti-strange quarks.

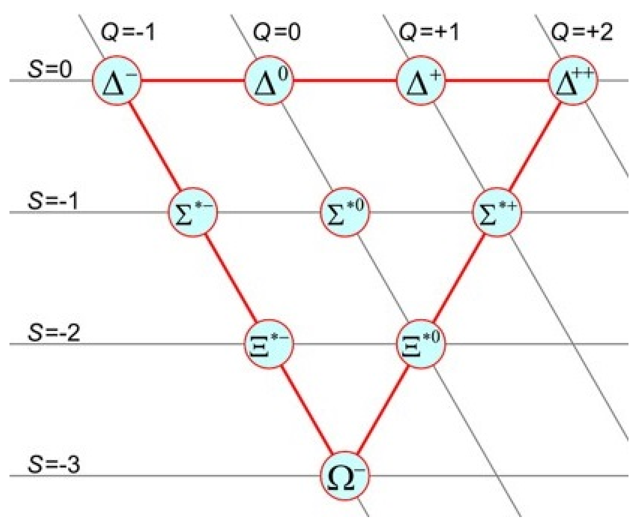

Figure 7: The light baryon decuplet.[10]

decuplet are composed of baryons containing up, down, and strange quarks. It is interesting to note that many of these particles are composed of the same quarks, such as the proton and Δ^+, both composed of two up quarks and a down quarks. The difference is the linear combination of these quarks, accounting for the different ways that the quarks can be "arranged" in the baryon. As such, the quark wavefunction of the two particles are[1]

$$p = \frac{1}{\sqrt{6}}(2uud - udu - duu)$$
$$\Delta^+ = \frac{1}{\sqrt{3}}(uud + udu + duu)$$

Thus, while the proton has a mass $m_p = (938.2720813 \pm 0.0000058)$ MeV and spin of $J_p = 1/2$, the Δ baryons have a mass of $m_\Delta = (1232 \pm 2)$ MeV and spin of $J_\Delta = 3/2$.[8] As a result, the Δ^+ baryon is called a higher-mass excitation of the proton. Though the proton is stable, Δ^+ has a mean lifetime of $\tau_{\Delta^+} = (5.63 \pm 0.14) \times 10^{-24}$ s with decays primarily to $\Delta^+ \to \pi^0 + p$ or $\pi^+ + n$, though the branching ratios are not yet known.[8] The difference in linear combination of composing quarks is also the reason why the three mesons grouped in Figure 5 with $S = Q = 0$, the neutral pion, and the eta and eta prime mesons, are all different particles made up of the same quarks.

2.4 Kinematics

In order to discover and identify new particles, particle physics experiments primarily analyse the kinematics of particle interactions. This allows for a calculation of the particle's mass, while the other particles involved in the interaction mean that the properties of the particle, such as electric charge and spin, can be determined. The universally fulfilled conservations of energy and momentum in a closed system are largely employed to calculate the mass of unknown particles. To do so, the masses and velocities of the other particles involved in the interaction need to be measured.

2.5 Bubble Chamber

The number of protons passing through the bubble chamber (in x direction) obeys

$$N(x) = N_0 e^{-n\sigma x} \tag{1}$$

with N_0 being the initial proton number, n the number density, σ the (total) cross-section.

3 Procedure

3.1 Magnification

We determined the magnification of the photographs by comparing the known coordinates of marks on the two glass planes with the measured distances and assuming the beam passes through the middle of the bubble chamber.[4] Table 1 contains the results.

Distance (cm):	F21 - F22	G41 - G42
calculated	23.9951	32.1905
measured	28.2 ± 0.1	37.7 ± 0.1
V_F, V_G	0.85089 ± 0.00302	0.85386 ± 0.00226
V_a	0.85238 ± 0.00264	

Table 1: Magnification

To get the true depth at which the beams were passing through, we used the "stereo-shift" method in 23 different cases. Viewing the same event from two different cameras, we measured the displacement s_G of the point G41 and s_A of an easily identifiable event in the path of the beam, both with an error of ± 0.1 cm. From the data gathered, we discovered the depth to be at

$$\frac{s_A}{s_B} = 0.5700 \pm 0.0209, \tag{2}$$

of the total depth, which is in disagreement with our assumption for the magnification before, namely that the beam passes through at 0.5 depth. This is an important source of systematical error when measuring length on the photo and reconstructing real distances from it.

3.2 Scattering events

For our next task, we analyzed 50 records, identifying and counting elastic and inelastic scatterings between the marks F21 and F35. Of the 532 total incoming protons, we found 27 of them interacted with the hydrogen in the chamber via elastic, and 64 via inelastic scattering. The number density is

$$n = \frac{\rho}{M_\mathrm{atom}} = \frac{2 \cdot 0.063 \frac{\mathrm{g}}{\mathrm{cm}^3} \cdot 6 \cdot 10^{23} \frac{1}{\mathrm{mol}}}{2 \frac{\mathrm{g}}{\mathrm{mol}}} = 3.78 \cdot 10^{22} \, \frac{1}{\mathrm{cm}^3}$$

The length between points F21 and F35 was measured to be (174.5 ± 0.1) cm, which gives a real distance of $L = (148.739 \pm 0.085)$ cm. The cross section can be calculated from

$$N(L) = N_0 e^{-\sigma n L} \implies \sigma = \frac{\ln \frac{N_0}{N(L)}}{nL}$$

For the total cross section, we have $N_\mathrm{t}(L) = 91 \pm 9$ (binomial distribution error), while for the elastic cross section, $N_\mathrm{e}(L) = 27 \pm 5$. These values yield

$$\sigma_\mathrm{total} = (9.264 \pm 1.783) \;\; \mathrm{mb},$$
$$\sigma_\mathrm{elastic} = (33.367 \pm 3.504)\,\mathrm{mb}.$$

4 Conclusion

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