Week 13: Particle Physics I (Undergraduate)

The goals of particle physics are to identify the fundamental constituents of the universe and to determine the nature of their interactions. Research over many decades has identified a multitude of subatomic particles, not all of which turned out to be fundamental. The first fundamental constituent, the electron, was discovered in 1897, by J.J. Thomson. Its antiparticle, the positron, was discovered in 1932, by Carl Anderson. Anderson, along with Seth Neddermeyer, discovered the muon, like the electron, a lepton, in 1936. Another sort of fundamental particle, quarks, were first identified in 1968. Interaction mediators are another type of fundamental particle. These include the photon, which was identified by Einstein in 1905; three weak bosons, surmised in 1968, and discovered in 1983; and eight gluons, which are never detected, but whose existence was confirmed in experiments from 1978 - 1980.

Classifying subatomic particles provides a way to understand their nature. It is now convenient to classify subatomic particles by their intrinsic spin and by how they interact.

Intrinsic spin allows particles to be classified as either fermions, which have half-integer spins ($n/2$, where n is an odd integer), and bosons, which have no or integer spin (n, where n is zero or an integer). Ordinary matter is composed of fermions. That is, electrons, protons, and neutrons are fermions. Photons, on the other hand, are bosons.

Fermions obey the Pauli exclusion principle: no two fermions "occupy" the same state, where "state" is described by quantum numbers, including energy, spin, angular momentum, and other quantum mechanical characteristics, as well as position (that is, the smallest region of space consistent with the Heisenberg uncertainy principle). With bosons, any number may occupy the same state. In fact, identical bosons tend to occupy the same state.

The present understanding of particle physics is summarized in the "Standard Model." This model identifies three sorts of fundamental (elementary) particles: leptons, quarks, and mediating bosons. The model contains six sorts of leptons, six sorts of quarks, and thirteen sorts of mediators. All leptons and quarks are spin-1/2 fermions; mediators are spin-1 or spin-2 bosons. A spin-0 boson, the Higgs particle, is responsible for the mass of each fundamental particle. Each lepton and quark is paired with its antilepton or antiquark. Since quark and antiquark combinations comprise all known non-leptonic subatomic particles, other than the mediating bosons and Higgs particle, this matter-antimatter pairing implies that all subatomic particles have corresponding antiparticles. To be clear, antiparticles have the same mass, spin, and lifetime as their particle partner, but have opposite electric charge and some opposite quantum numbers. Some neutral particles, such as the photon and the π^0 meson, are their own antiparticles.

Quarks are distinguished from leptons by the fact that quarks are subject to the strong interaction as well as the electromagnetic, weak, and gravitational interactions, while leptons are subject only to the last three of these (that is, not the strong interaction). Furthermore, quarks have fractional charges (relative to the charge of the proton), while leptons have integer charges. Each quark has a "baryon number" of $+\frac{1}{3}$ and each antiquark has a baryon number of $-\frac{1}{3}$.

The Standard Model classifies leptons (and antileptons) and quarks (and antiquarks) into three families–or generations–according to various quantum numbers. In the case of leptons, these quantum numbers include electron number (L_e), muon number (L_μ), and tau number (L_τ). Each family consists of a charged lepton and a neutral lepton (neutrino).

Leptons						
family	lepton	Q	L_e	L_μ	L_τ	mass [MeV]
I	e	-1	1	0	0	0.511
	ν_e	0	1	0	0	$< 2 \times 10^{-6}$
II	μ	-1	0	1	0	106
	ν_μ	0	0	1	0	< 0.2
III	τ	-1	0	0	1	1777
	ν_τ	0	0	0	1	< 18

Q indicates charge. Antilepton quantum numbers are the negative of these lepton quantum numbers.

Quark classification quantum numbers include strangeness (S), charm (C), beauty or bottomness (B), and truth or topness (T). Each family consists of a $-1/3$ charge quark and a $+2/3$ charge quark.

Quarks							
family	quark	Q	S	C	B	T	mass [MeV]
I	d	$-1/3$	0	0	0	0	≈ 5
	u	$+2/3$	0	0	0	0	≈ 2
II	s	$-1/3$	-1	0	0	0	≈ 100
	c	$+2/3$	0	1	0	0	≈ 1200
III	b	$-1/3$	0	0	-1	0	≈ 4200
	t	$+2/3$	0	0	0	1	≈ 174000

Mediators are associated with interactions: the photon with electromagnetism, two charged ($W^\pm$) and one neutral (Z^0) weak vector bosons with the weak interaction, eight gluons (identical except for their "colors") with the strong interaction, and the graviton with gravitation (no more will be said regarding gravitation).

Quarks are never found in isolation, but almost only in groups of three or in quark-antiquark pairs. An ensemble of three quarks is referred to as a baryon; an antibaryon is an ensemble of three antiquarks. Quark-antiquark pairs are known as mesons. Evidence exists of 4-quark and 4-quark + 1-antiquark objects, exotic ensembles allowed in the Standard Model. Of course, the Standard Model "explains" this state of affairs. In fact, it defines baryons and mesons (originally, "heavy particles" or "intermediate-mass particles," while leptons were "light mass" particles) according to their quark content:

- Baryons are composed of three quarks, and antibaryons are composed of three antiquarks.
- Mesons are composed of a quark and an antiquark (antimesons are composed of an antiquark and a quark).

Being composed of three fermions, baryons are fermions; mesons, composed of quark-antiquark pairs) are bosons.

1. Complete the spin-$\frac{1}{2}$ baryon octet, formed from the three lightest quarks, u, d, and s.

qqq	Q	S	Baryon	Lifetime [s]	Typical Transformation
uud	$+1$	0	p	stable	N/A
udd	0		n	9×10^2	$p + e^- + \bar{\nu}_e$
uds			Λ^0	3×10^{-10}	$p + \pi^-$ or $n + \pi^0$
uus		-1	Σ^+	8×10^{-11}	$p + \pi^0$ or $n + \pi^+$
			Σ^0	7×10^{-20}	$\Lambda^0 + \gamma$
			Σ^-	1×10^{-10}	$n + \pi^-$
			Ξ^0	3×10^{-10}	$\Lambda^0 + \pi^0$
		-2	Ξ^-	2×10^{-10}	$\Lambda^0 + \pi^-$

2. Complete the spin-$\frac{3}{2}$ baryon decuplet, formed from the three lightest quarks, u, d, and s.

qqq	Q	S	Baryon	Lifetime [s]	Typical Transformation
uuu	$+2$	0	Δ^{++}	6×10^{-24}	$p + \pi^+$
		0	Δ^+	6×10^{-24}	$p + \pi^0$ or $n + \pi^+$
			Δ^0	6×10^{-24}	$p + \pi^-$ or $n + \pi^0$
			Δ^-	6×10^{-24}	$n + \pi^-$
		-1	Σ^{*+}	2×10^{-23}	$\Lambda^0 + \pi^+$ or $\Sigma^+ + \pi^0$ or $\Sigma^0 + \pi^+$
			Σ^{*0}	2×10^{-23}	$\Lambda^0 + \pi^0$ or $\Sigma^+ + \pi^-$ or $\Sigma^0 + \pi^0$
			Σ^{*-}	2×10^{-23}	$\Lambda^0 + \pi^-$ or $\Sigma^0 + \pi^-$ or $\Sigma^- + \pi^0$
			Ξ^{*0}	7×10^{-23}	$\Xi^0 + \pi^0$ or $\Xi^- + \pi^+$
dss			Ξ^{*-}	7×10^{-23}	$\Xi^0 + \pi^-$ or $\Xi^- + \pi^0$
			Ω^-	8×10^{-11}	$\Lambda^0 + K^-$ or $\Xi^0 + \pi^-$ or $\Xi^- + \pi^0$

3. **Complete the pseudo-scalar (spin-0) meson nonet, formed from the three lightest quarks, u, d, and s.**

$q\bar{q}$	Q	S	Meson	Lifetime [s]	Typical Transformation
$u\bar{u}$	0	0	π^0	9×10^{-17}	$\gamma + \gamma$
			π^+	3×10^{-8}	$\mu^+ + \nu_\mu$
			π^-	3×10^{-8}	$\mu^- + \bar{\nu}_\mu$
$d\bar{d}$			η	5×10^{-18}	$\gamma + \gamma$ or $\pi^0 + \pi^0 + \pi^0$ or $\pi^+ + \pi^0 + \pi^-$
		+1	K^+	1×10^{-8}	$\mu^+ + \nu_\mu$, $\pi^+ + \pi^0$, $\pi^0 + e^+ + \nu_e$, or $\pi^+ + \pi^+ + \pi^-$
			K^0	*	*
			K^-	1×10^{-8}	$\mu^- + \bar{\nu}_\mu$, $\pi^- + \pi^0$, $\pi^0 + e^- + \bar{\nu}_e$, or $\pi^- + \pi^- + \pi^+$
		-1	$\overline{K^0}$	*	*
$s\bar{s}$			$\eta^{'}$	3×10^{-21}	$\pi^+ + \pi^- + \eta$ or $\rho^0(\pi^+ + \pi^-) + \gamma$ or $\pi^0 + \pi^0 + \eta$

***The K^0 and $\overline{K^0}$ are strong eigenstates which can't transform (due to strangeness conservation) via the strong interaction. Each is a linear combination of the weak eigenstates K^0_S and K^0_L, and the weak interaction does not conserve strangeness. The K^0_S has a lifetime of 9×10^{-11} s and typically transforms into $\pi^+ + \pi^-$ or $\pi^0 + \pi^0$. The K^0_L has a lifetime of 5×10^{-8} s and typically transforms into $\pi^\pm + e^\mp + \bar{\nu}_e/\nu_e$, $\pi^\pm + \mu^\mp + \bar{\nu}_\mu/\nu_\mu$, $\pi^0 + \pi^0 + \pi^0$, or $\pi^+ + \pi^0 + \pi^-$.**

4. **Why is the proton charge +1? The neutron charge 0?**

5. **Explain why baryons are fermions and mesons are bosons?**

6. **The positive kaon (K^+) has charge +1, spin 0, and strangeness +1. Explain.**

7. **The Ξ^0 (cascade-0) has charge 0, baryon number +1, and strangeness −2. Explain.**

8. **Graph the spin-$\frac{1}{2}$ baryon octet as follows:**
   - **Three rows for strangeness, $s = 0$, $s = -1$, and $s = -2$.**
   - **Three diagonal (\) columns for charge, $Q = -1$, $Q = 0$, and $Q = 1$ (the first column starts in the second row; the third column ends in the second row).**

- **Two particles should occupy the middle point (second row/second column).**
- **Label each row with the strangeness, each column with the charge, and each point with the particle symbol.**

9. **Graph the spin-$\frac{3}{2}$ baryon decuplet as follows:**
   - **Four rows for strangeness, $s = 0$, $s = -1$, $s = -2$, and $s = -3$.**
   - **Four diagonal (\) columns for charge, $Q = -1$, $Q = 0$, $Q = 1$, $Q = 2$ (the second column ends starts in the third row; the third column ends in the second row, and the fourth column occupies only the first row).**
   - **Label each row with the strangeness, each column with the charge, and each point with the particle symbol.**

10. **Graph the pseudo-scalar (spin-0) meson nonet following guidelines like those of the spin-$\frac{1}{2}$ baryon octet, except that now three particles occupy the center point.**

In the Standard Model, intermediate vector (spin-1) bosons mediate the interactions fermions undergo: the interactions of leptons and quarks is modeled as the emission and absorption of intermediate vector bosons. A coulombic interaction between two charged particles is a photon exchange; quarks form hadrons due to the exchange of gluons; particles transform because leptons and quarks exchange weak bosons.[1]

This model of interactions as particle exchanges was introduced by Hideki Yukawa around 1935, when he proposed the exchange of certain mesons (now called pions) as the interaction holding the nucleus together. These mesons would manifest out of the vaccum for so short a time that energy conservation could be temporarily violated, but in accordance with the Heisenberg uncertainty principle.

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

The time, $\Delta t = \frac{\hbar}{2\Delta E}$, is too short to measure the violation, allowing the temporary existence of a particle with mass up to $m = \Delta E$. Obviously, the larger the mass, the shorter its existence, and the shorter the range of the interaction

$$R \lesssim c\Delta t$$

where c is light speed.

Since the meson is emitted and absorbed in too little time to measure its characteristics, it is known as a virtual particle: it can't be directly detected, but its effects can be.

[1] By exchanging (spin-0) Higgs bosons, fundamental particles obtain mass.

11. Estimate the mass in MeV of the pion, assuming it moves ≈ 1 fm at speed c.

When viewed as nucleons, protons and neutrons differ only by charge,[2] and the strong interaction is of equal strength between any pair of nucleons. Recognition of this led Heisenberg to propose that they were just different eigenstates of the same object, much like spin-up and spin-down electrons. The different eigenstates were designated isospin states, also up (proton) and down (neutron). The Yukawa interaction, then, allowed flipping as well as conserving these states. Thus, a proton can transform into a neutron by emitting a positive pion, which is then absorbed by a neutron, transforming it into a proton. Negative pion emission by a neutron leaves it a proton; the proton's subsequent absorption of the pion makes it a neutron. Neutron-neutron and proton-proton interaction are mediated by a neutral pion. This means that the pion had to have three states, positive, negative, and neutral, an isospin triplet, requiring an (total) isospin of 1. There are therefore three pion states distinquished by I_z components $I_+ = +1$, $I_0 = 0$, and $I_- = -1$.

With further experimental and theoretical developments in particle physics, in particular the determination that protons and neutrons are in fact composite objects, the Yukawa interaction was replaced by Quantum Chromodynamics, in which the strong force is modeled as the exchange of gluons between quarks, and the nuclear force is seen to be a residual outcome of this interaction. Nevertheless, the exchange model remains intrinsic to quantum field theory, the basis of all interaction descriptions in the Standard Model.

[2] The small mass difference between them was attributed to the additional electrostatic potential in the proton–even though the sign of the mass difference contradicts this explanation: being repulsive, the Coulomb potential should cause the proton to have less binding energy and therefore a bigger mass, and be less stable than the neutron, all of which is wrong.