Fundamental Particles

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1 Cosmic Rays & Antiparticles

We have established, by now, that protons, neutrons and electrons alone are not the fundamental building blocks of the universe. So, how far can we break down matter?

1.1 Cosmic Rays

Scientists working on electroscopes first noticed that they seemed to discharge much faster than they could account for. At the time, it was suggested that there could be background radiation from the Earth interfering with it. This is a very testable hypothesis, and a guy called Victor Hess tested it by going into a high altitude balloon with an electroscope and taking measurements on the way up. If the radiation is coming from the Earth, it should become less noticeable as you move away from Earth. Surprisingly, Hess saw the opposite; it become greater the higher up he went. He concluded that therefore, the radiation was not coming from Earth, but from space. We call this **cosmic radiation**.

1.2 Paul Dirac, the Discovery of Antimatter, and Mathematical Beauty

Modern physics is split into three categories. Classical (think: Newton, Kepler) deals with the everyday stuff. It is very useful and a very good approximation, but is not very accurate in extreme circumstances; the very big, the very small, the very fast, the very cold; classical physics starts to fail. Quantum physics is excellent for describing the very small; think fundamental particles, on the atomic and sub atomic scale. We've found nothing better for the small things yet, but it doesn't scale up well at all. For the very big and very fast (think stars, black holes, things that can travel close to/at the speed of light) we use something called relativity. Relativity is outside the scope of the LC, but it is what made Albert Einstein a household name. I will add that relativity itself has two sections: General Relativity (GR) deals with everything, regardless of how massive, or if it's accelerating. A subset of problems can be solved using the simpler special relativity, which is GR, but doesn't take into account acceleration or large masses. This makes it a lot easier to work with, but isn't as comprehensive.

Problem: the theories for the very big and the very small don't seem to meet in the middle. They regularly have disagreements. For the past century, physics has been cleaved brutally in half. Many efforts have been made to unite them in what we would call a **Grand Unifying Theory/ Theory of Everything**. We have not yet found such a theory, but that doesn't mean we haven't made progress.

In 1928, British theoretical physicist Paul Dirac was trying to make a little bit of progress on this very problem. He started to formulate what is now called the Dirac Equation. To understand the Dirac Equation, you would need first an understanding of advanced quantum mechanics and special relativity. These prerequisites are outside the scope of this course. For brevity, I'll skip to the working end.

Dirac wanted to make a mathematical equation to describe an electron moving in some arbitrary electric field (think of it in the style of F = ma, from which you could derive lots of information about the situation from a little maths), taking into account both quantum mechanics and special relativity. When doing so, he noticed something extremely peculiar; the equation was absolutely horrible to work with if he only allowed the electron to have a negative charge. As we saw earlier, electrons always have negative charge. If he allowed charge to be positive and negative (like the positive and negative answers to a square root), the equation simplified beautifully. This, of course, implies the existence of a positively charged electron. The Dirac equation also implied the existence of other types of antiparticles; particles that had equal masses to other, known particles, but opposite charges. We call this type of matter 'antimatter'. With no evidence aside from mathematical beauty, Dirac predicted the existence of antimatter - 'inverse' matter that never before been seen.

And the absolute madlad got it right.

Five years later in 1932, a positron was found in an experiment by accident. While trying to study cosmic rays, C.D. Anderson detected what had the same mass as an electron, but a positive charge, which could only be explained by the Dirac Equation. Dirac was awarded the Nobel Prize the following year for his discovery.

1.3 Antimatter Annihilation & Pair Production

The 1930s saw some more investigation into newly found antimatter. First up, how is antimatter created?

Once again, the answer is mass-energy equivalence. If a very high energy photon (think x-rays) grazes a nucleus, sometimes, the photon seems to disappear and is converted into two particles of equal mass (mass-energy is conserved) and opposite charge (so overall charge is conserved). To conserve momentum, the two particles move at the same speed in opposite directions. Now you have one electron and one positron. The process is called **Pair Production**.

We can also go in the other direction. If an electron and a positron collide, the 'cancel' eachother out and will reform the photon. This process is called **Antimatter Annihilation**.

2 High Energy Collisions & The Particle Zoo

Okay, so that covers electrons and positrons. But we established earlier that there were other types of antiparticles, how are they created? What do they produce when they annihilate?

Let's look at protons. A proton is around 2,000 times heavier than an electron, so pair production for a proton and an antiproton takes immense energy. In 1955, Segré and Chamberlain did it; they used a 6.4GeV proton beam to bombard a copper target. They produced a whole host of weird particles, and among them, they detected an antiproton.

It turns out that when a proton and an antiproton collide, they don't produce a photon, but new types of particle pairs. One such process produces what is called a **pion-antipion pair**. Pions tend to decay fairly quickly, but can sometimes be found after being created by incoming cosmic rays colliding with the atmosphere.

Something strange is that, if you actually look into the natural universe, you will not find antimatter. We can create antimatter in labs on earth fairly easily; we do it all the time. Theoretically, there is nothing preventing the existence of antiatoms, with a nucleus made of anti-protons which is orbited by positrons. But it does not occur in nature. We don't know why not.

2.1 The Particle Zoo

The pion wasn't the only new particle type found in cosmic rays. Next up are the muons and neutrinos. Pions decay into one muon and one neutrino in 10^{-8} seconds. Muons in turn decay into an electron and two neutrinos in 10^{-6} seconds.

Physicists kept messing around, trying to make new types of fundamental particles, until by the 1906s, over 200 new particles had been found. It was difficult to believe that there really were this many fundamental particles, and there was no solid classification system for these particles. The goal, at this point, was to create some kind of chart along the same vein as teh periodic table to classify all the fundamental particles.

CERN, by the Swiss-French border, was established to get a firmer grasp on this. CERN is still in operation today and has made fantastic strides in the development of particle physics.

3 The Fundamental Forces

We know of four fundamental forces in nature. Two of these you will already be familiar with, but two will be new to you. These two were discovered

- Gravitational - this is the force that causes an interaction between matter. It is what keeps your feet on the floor, the Earth in orbit around the sun, the tides rising and falling. You know this one from your day-to-day life. You may be surpised to learn that it's the weakest of the forces; it takes immense masses (planet sized) for it's effects to be noticeable. Sub-atomic particles have small masses, and so their gravitational pull is negligible. It is inversely proportional to the square of distance.
- Electromagnetic - we spent a lot of time looking at this is previous weeks. This is the force that causes magnets to attract, keeps current flowing in a circuit, and holds atoms together. It is also inversely square proportional.
- Strong Nuclear - Here's new force number 1. This force acts between protons and neutrons to hold the nucleus together. It is immensely strong (the clue is in the name), but it only works on very, very small distances - outside the nucleus it cannot be felt.
- Weak Nuclear - The last new force is found in radioactive decay. It is responsible for the decay of beta particles. It is short range, and weaker than the strong nuclear force, but still stronger than electromagnetic and gravitational.

4 The Ultimate Structure of Matter (we think)

Now, I'm going to show you what progress we've made on building that 'periodic table for particles'.

Sub-atomic particles seem to be split into two categories; **hadrons** (nuclear particles) and **leptons** (non-nuclear particles).

4.1 Hadrons

Hadrons are all the particles subject to the strong force. There are over 200 types of hadrons, but these are split themselves into two particles: the 'baryons' and the 'mesons'.

4.1.1 Baryons

Baryons are hadrons that have large mass. Protons ad neutrons (neucloens) fall into this category. Other strange particles called 'hyperons' are found here too. Hyperons have very short lifespans and decay into nucleons and mesons. They are composed of a set of three quarks - we'll talk more about these in a moment.

4.1.2 Mesons

Mesons are particles with masses between that of an electron and a proton. The strange particles we saw earlier, like pions and kaons. Mesons are composed of a quark and an antiquark.

4.2 Quarks

With hundreds of different new particles found, there seemed to be very little order in the discoveries. Murray Gell-Mann (an important figure in modern physics) named a new type of particle - the **quark**. The name is a reference to James Joyce's *Finnegan's Wake* - "Three Quarks for Muster Mark" (Gell-Mann was an avid reader with an interest in linguistics).

Quarks are like building blocks for heavier particles. There are six types - up, down, strange, charmed, top and bottom. Each type also has a corresponding antiquark. The below table as the 6 quarks and their charges. To find the charges of the antiquark, just change the sign of the charge.

Quark	Symbol	Charge
up	u	$+^2/_3$
down	d	$-^1/_3$
charm	c	$+^2/_3$
strange	s	$-^1/_3$
top	t	$+^2/_3$
bottom	b	$-^1/_3$

So for example, to make a proton, you need two ups and a down (uud). For a neutron, you need an up and two downs (udd). A pion is an up and an antidown ($u\bar{d}$) and an antipion is an antiup and a down ($\bar{u}d$).

4.3 Leptons

Leptons are the fundamental particles not subject to the strong force. There are 6 types in total: electron, electron neutrino, negative muon, muon neutrino, negative tau, and tau neutrino. Each one, as usual, has a corresponding antiparticle.

5 Summary of Fundamental Particles

So now, we have six quarks, six anti quarks, six leptons and six antileptons. These particles make up all matter.

The only thing missing from our little table are the force carriers. These don't seem to show on the LC syllabus, probably because it's still an open are a of study. Our table is not complete; but stay tuned with the goings on in CERN and Fermilabs over the next few decades. A breakthrough seems overdue.