The Mysterious World of Particle Physics

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As medical professionals, we are familiar with various diagnostic imaging modalities and the use of radiation for therapy. Application of diagnostic imaging and treatment modalities including conventional radiography, CT, MR, PET scans, gamma knife, X knife etc., depends on an understanding and control of the fundamental physical processes involved. As 'End-users', we tend to focus on the practical aspects and care less about the fundamental processes involved. The countless efforts of basic research scientists and physicists have benefited the medical profession and our patients. A glimpse into the latest findings in particle physics and cosmology may be interesting.

At the beginning of the last century, the prevailing view amongst scientists was that humans had mastered nearly all the knowledge in Physics. It was thought that all matters in the universe were made up of two fundamental particles, the proton and the electron. Scientists were complacent because the model was simple, symmetrical and aesthetically pleasing. This was soon overturned by the introduction of quantum physics and general relativity. There remained huge gaps in our knowledge and lots of areas for research in physics. Now we know that we might understand less than 5% of our universe!

Scientists investigate the composition of matter simply by smashing it apart, like what curious kids would do to their toys. Hence they construct particle accelerators with ever increasing energies. The purpose of these monstrous machines is to accelerate matters to near the velocity of light (the limiting velocity in the universe) before smashing them apart to find out about the constituents. The Large Hadron Collider (LHC) which had attracted media and public attention recently, is currently the world's largest particle accelerator with the highest energy. It was suggested by the media that it might recreate the condition of the Big Bang and mini black holes. It crosses the border between Switzerland and France. It aims to provide enough collision energy to find a key particle called Higg's Boson which will substantiate the validity of what scientists called the standard model. What is the standard model then?

By the late 1960s, more than a hundred particles apart from the ones we are familiar with (protons, neutrons and electrons) were found and the simple atomic model we learnt was turned into chaos. Through long series of experimental and theoretical studies, order was slowly restored amongst chaos. According to the latest standard model in particle physics, there exists a very simple scheme of two classes of particles - the quarks and leptons, and a set of fundamental forces that allow them to interact with each other. These 'forces' are regarded as being transmitted through the exchange of particles called gauge bosons. The photon is a gauge boson which transmits the electromagnetic force. These fundamental particles form various combinations that are observed today as neutrons, protons and the various particles seen in particle accelerators.

The following is a simplified scheme of the standard model:

Fundamental particles

	Quarks	**Leptons**
Family one	**u** - up quark **d** - down quark	**e** - electron ν_e - electron neutrino
Family two	**c** - charm quark* **s** - strange quark	μ - muon ν_μ - muon neutrino
Family three	**t** - top quark **b** - bottom quark	τ - tau ν_τ - tau neutrino

Force carriers (the gauge bosons)

Force	**Relative strength**	**Gauge boson (carriers)**
Strong	1	Gluon
Electromagnetic	1/137	Photon
Weak	10^{-9}	W^+, W^-, Z
Gravity	10^{-38}	Graviton

The standard model is the theory that describes the role of these particles and the interactions between them to produce the tangible matters in our universe. The names of the particles carry no literal meaning. Scientists just want to give them an identity. Their properties have nothing to do with e.g. positions (up, down) or attractiveness (strange, charm)!

The proton that we are familiar with consists of two up quarks and one down quark, while the neutron consists of two down and one up quark. Thus the up and down quarks together with the lightest lepton - the electron make up most of the known matters of our universe. What then, is the purpose of having the other two families? No one has yet the definite answer. The existence of more than one family of particles was predicted by theorist in the 70s. The 2008 Nobel Prize in Physics was awarded in part to two Japanese physicists - Kobayashi and Maskawa; for predicting the existence of at least 3 families of quarks & leptons in the early 1970s. You have to stay healthy to wait for your Nobel Prize. The particles of the other families were then discovered in particle accelerator experiments. The last one to unfold itself was the top quark, discovered at the FermiLab in Chicago in 1995. Its average lifetime is about 10-25s! Despite its short lifespan, its discovery is an important substantiation of the standard model.

Four fundamental forces mediate the interactions of these particles; electromagnetism, weak nuclear force, strong nuclear force and gravity.

We are most familiar with electromagnetism and gravity in our everyday world. We normally feel only the effect of gravity but not electromagnetic force because the universe is on the whole neutral; i.e. there is a balance of positive and negative charges. Gravity is ubiquitous. It acts on all matters to infinity but is weakest in strength. We can easily overcome the gravitational pull of the whole mass of the earth on any small object by simply picking it up with minimal effort. It is most important in defining the shape and structure of the whole universe. All matters in the universe are bound by gravity. Electromagnetic force also acts to infinity. It differs from gravity in that it can be attractive or repulsive, while gravity always attracts. Electromagnetic force is much stronger than gravity (by 1036 orders of magnitude). We don't feel it because of an exact balance between opposite charges. If a person standing at an arm's length has 1 % excess of electrons than protons, the resulting net electric force would be sufficient to lift the weight of the entire earth! The strong nuclear force binds quarks together and holds neutrons and protons in their atomic nuclei. The weak nuclear force mediates radioactive decay.

There is substantial evidence and experimental basis for the validity of the standard model. If all these seem dull and confusing, the followings might stimulate some sense of awe and points to ponder:

1. One might wonder what the shapes of these particles are. The leptons are quarks have all defined masses. However, they are regarded as points without a volume.

2. A single quark cannot be isolated. Quarks are permanently confined in the protons and neutrons. They carry fractional electric charges. (e.g. up quark charge 2/3, down quark - 1/3; making up the +1 charge of a proton and neutrality of the neutron).

3. All matters possess particle and wave properties, depending on how we 'look at' them even though in the macroscopic world, we see them usually as particles.

4. The positron used in PET scan is a positive electron, a kind of antimatter. There exist antimatter counterparts to all the matters i.e. antiprotons, antineutrons make up of anti-up, anti-down quarks; antineutrinos etc. They have the same mass but opposite charge to their counterparts. It was believed that matter and antimatter were created from energy in almost equal amounts in the early universe according to the famous Einstein equation E = mc2 (energy equals mass times the square of velocity of light). Particles and antiparticles are extremely inhospitable. They annihilate each other, turning back into energy. A tiny excess of matter over antimatter in the early universe result in the exclusive presence of matter in the current Universe. For every 109 antimatter particles, there were 109 + 1 matter particles. We owe our existence to this tiny imbalance in ratio.

5. It is believed that all matters in the universe, including space and time were created 13.7 billion years ago in a 'big bang'. Around 10-37 seconds after the moment of creation, the universe underwent a moment of inflation, lasting for 10-32 seconds. During this cosmic eyeblink, the universe expanded exponentially by a factor of 1040 to 10100! The surge in fuel price is nothing compared to cosmic inflation!

6. Why should there be three families of quarks and leptons? The first family makes up all the visible matters in the observable universe. The other two families exist only briefly at the moment of creation of the universe, in some exotic places of the universe, and in man-made particle accelerators. One of the famous remarks was made by Isador I Rabi (Nobel Prize Physics 1944). When the muon was discovered, he exclaimed, "Who ordered that?"

7. There is compelling evidence from current cosmological observations and research which suggest that leptons and quarks make up at most about 4% of the universe. About 22% of the universe is believed to consist of some unknown dark matter, and 74% of the universe consists of some mysterious dark energy. Explaining the nature of dark energy is one of the great mysteries in modern physics. After all, we seem to know only about 4% of the universe.

8. Hydrogen and helium made up all the elements of the early universe. The carbon atoms present in our bodies had to be 'made' by nuclear fusion in the core of one of the first generation of stars. After an explosion of one of these first generation stars in the vicinity of our solar system, a second generation star (our sun) formed under gravity with heavier elements, allowing the formation of planets with elements for life. We are all (the atoms making up our bodies) manufactured and once closely packed in the core of another star!

In a nutshell, this is a simplified view of the standard model accepted by physicists nowadays. We don't actually need to know the theories behind all these. We might as well stay in our cozy homes to enjoy the benefits of technological advance from other people's effort. If JJ Thomson had not discovered the electron in a small lab in Cambridge in 1897, we will not even have televisions.

* Professor Samuel Ting (丁肇中), was one of the co-discoverers of the charm quark (Nobel prize in Physics 1976); making up the J particle - after his family name as the letter J in the English alphabet resembles the Chinese character '丁' .