Our Particle Universe

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Ever since the discovery of the electron more than 100 years ago, scientists have asked the questions –"what is our universe made of?" and "why is the universe the way it is?" Not long before, it was found that these two questions are related to each other. The interactions of particles in the universe determines its evolution, its very form, and existence. In this article, we will trace the discovery of some of these particles, learn about their interactions, and try to understand their properties such as electric charge and mass.

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1. Introduction: Atoms, the Starting Point

In early science classes, you would have learned that the atom consists of a central nucleus and negatively charged electrons. The nucleus contains both positively charged protons and neutral neutrons. The charges of the proton and electron are considered to be exactly equal and opposite, so that the atom is electrically neutral as a whole.

We know that atoms are too small to be seen with the naked eyes. How could these things then be deduced? It was known from the work of many chemists such as Dalton, Dobereiner, Newland, and Mendeleev that elements always interact in ratios of small whole numbers to form compounds. This observation brought to light notions such as atomic number and mass number. However, the first estimate of the size of atoms came from a very unlikely source – Albert Einstein. In one of his famous papers of 1905, Einstein had considered 'Brownian motion'. Brown had noticed that pollen grains in water are continuously on the move, but could not find out the governing mechanism. Einstein showed that this happens because the pollen grains are being continually bombarded by the water molecules. He wrote a diffusion equa-

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tion for the movement of these so-called Brownian molecules, and used this to estimate the size of the molecules as well as Avogadro's number [1] [1]. An experimental verification of this theory by Jean Perrin in 1908 convinced people that atoms and molecules exist, and Perrin got the Nobel Prize in Physics in 1926[2].

[1] Number of molecules in a mole. Molecular weight expressed in grams of the substance.

[2] Note that 1926 was a special year for the discovery of quantum mechanics!

As Perrin was busy verifying Einstein's theory, J J Thomson studied cathode rays and showed that they were made of electrons that were 1,800 times lighter than hydrogen. Electrons were the first subatomic particles to be discovered, and Thomson was awarded the Nobel Prize in 1906. From this point on, no more were atoms considered indivisible. Thomson however, did not correctly predict the atomic shape. He thought that electrons were distributed like raisins in a cake of positively charged distribution[3]. Current experiments show that the charge difference between electron and protons is less than $1\times10^{-21}\, e$, where e is the charge of the proton.

[3] How do you know that the atom is electrically neutral? There have been many tests of the atom's neutrality. One of them you can do yourself. Let us say that humans are mostly made of water. A water molecule has a molecular weight of 18, so 18 gms of water contain $N_A = 6.02 \times 10^{23}$ molecules. Use your weight to find the number of molecules and hence protons in your body, and see how large (rather small) a difference in electron and proton charge can be tolerated before it shows up as a large charge imbalance in our daily life!

1.1 *Scaling Property: Peeling the Layers to Find Out What Lies Inside*

Soon Rutherford discovered the nucleus, from the famous scattering of alpha particles on gold nuclei [2]. The radius of a nucleus is expressed in fermi, 1 fm $= 10^{-5}$Å. The radius of a nucleus of mass A behaves as $R = R_0 A^{1/3}$, where $R_0 \sim 1$ fm, so there is not much difference between the size of the alpha particle and the gold nucleus. This scaling or matching property is what gave Rutherford the clue to the existence of nuclei. To understand this better, let us go back to Heisenberg's uncertainty principle, which gives a bound on the product of the uncertainty in momentum and position (or energy and time) in terms of Planck's constant, h,

$$(c\Delta p)\times(\Delta x) \quad \geq \frac{\hbar c}{2}\ , \quad \text{or,} \quad (\Delta E)\times(c\Delta t) \quad \geq \frac{\hbar c}{2}\ ,$$

where $\hbar = h/2\pi$, and we have inserted the constant velocity of light so that the two statements are dimensionally same. The constant $\hbar c$ can be computed in so-called natural units as $\hbar c =$ 197 MeV fm, where 1 MeV $= 10^6$ eV and 1 fm $= 10^{-15}$ m. This immediately tells us that the energy needed to probe an atom's nucleus with a length scale ~ 1 fm $\equiv 10^{-15}$ m is about 10^5 times larger[4] than that needed to probe an atom of size $\sim 1\text{Å} \equiv 10^{-10}$ m. The energy needed to remove an electron from a hydrogen atom is 13.6 eV; hence the energies involved in nuclear transitions are in MeVs (with no interactions with in-between energies).

[4]In other words, if you want to probe a smaller length scale, you need larger energies and *vice versa*. Since five orders of magnitude separate the atomic and nuclear scales, it means that the atom is almost hollow. A physical way to think of it is that if the nucleus of a hydrogen atom occupies the classroom where this author teaches (in Chennai), then its partner electron is somewhere in the vicinity of Mumbai!

So, we see that scales in physics determine the nature of interactions. This is a theme that recurs in particle physics. For instance, a similar scaling property showed that the nucleus was made up of smaller constituents (protons and neutrons) collectively called 'nucleons' and again, that nucleons are made up of constituent 'quarks'. But first let us examine the nature of interactions.

2. The Nature of Interactions

What holds the hydrogen atom together? The obvious answer is the Coulomb interaction between the positively charged proton and the negatively charged electron. The stability of this electromagnetic interaction (EM) is indicated by the fact that 13.6 eV of energy is required to separate them. This is the energy of binding of the atom, but is very difficult to measure since it is small compared to the mass of the atom (which is about 1000 MeV).

What holds the nucleons in the nucleus together? These are called strong interactions; strong because they have to overcome the Coulomb repulsion between protons and hold them together. This is why heavier atoms have progressively more neutrons in them than protons. Again, energy is released when the nucleus of an atom is bound together. This binding energy is about 7 MeV per nucleon and is therefore large and observable[5].

[5]It was Aston [3] who first made the observation in 1920 that the mass of a helium nucleus is less than that of four protons and attributed this to binding energy.

From this, we get the first hint that interaction energy can change the (perceived) mass of a particle. Many physicists speculated that the entire mass (actually, the mass energy, $E_m = mc^2$, as given by Einstein in his famous equation) of the particle is due to its interactions. The earliest theory was that its mass is due to purely electromagnetic interactions. If you consider an electron to be a sphere of radius a with its entire charge distributed on its surface, you can compute the energy density in the electric field,

$$u_{elec} = \epsilon_0 E^2/2,$$

from $E = q/(4\pi\epsilon_0 r^2)$ at a distance r.

The total energy in the electromagnetic field can be found by integrating the density over all space (r from a to ∞) to get $U_{elec} = (1/2)(e^2/a)$, where $e^2 \equiv q^2/(4\pi\epsilon_0)$ [4]. The associated mass energy should be $U_{elec} = mc^2$, and hence the mass can be identified. However, this varies, depending on the shape of the charge distribution. Perhaps this can be adjusted by defining things relativistically? Or even by defining a quantum description of electrodynamics? The real problem[6] is that once you ascribe a structure to the electron, like a finite size, you must ask, what holds this structure together, and so there has to be an additional force whose effect will also modify the mass. Hence, this beautiful idea was abandoned.

[6] So the notion of mass is much more complex than its definition in classical mechanics. The notion of charge is no less complex. Why is charge always found in units of the proton charge? This is called charge quantisation. We don't really know, though the presence of a magnetic monopole can cause such a quantisation to occur. No such monopole has yet been found.

Today we know that a completely different mechanism is at work– the 'Higgs mechanism'– to give mass to the elementary particles. So mass of particles such as electrons and quarks indeed arises due to interactions, but due to a new interaction called the 'Yukawa interaction' between such spin-1/2 fermions and the Higgs field.

3. What are Elementary Particles?

The three-quark state reflects a new quantum number that these particles possess, called the 'colour charge', which permits quarks to interact *via* strong interactions, just as having electric charge allows them to participate in electromagnetic interactions.

Elementary particles are those that are not composite. For instance, the proton (and neutron) are made of quarks, with a minimum of three quarks *uud* (*ddu* for neutrons). Here the u and d quarks have fractional charges $2/3$ and $-1/3$ of the proton charge, thus making up the right charge for protons and neutrons, which are called ' baryons'. The three-quark state reflects a new quantum number that these particles possess, called the 'colour charge', which permits quarks to interact *via* strong interactions, just as having electric charge allows them to participate in electromagnetic interactions. Colour charge is of three kinds, usually denoted as red, blue, and green, so that the three quarks together can form a colourless object which is what is seen in Nature.

Hence, electrons and quarks are elementary; nucleons are not. So the entire mass of the elementary electrons and quarks arises from interactions with the Higgs boson, while that of nucleons and pions[7] has additional contributions due to strong interactions. This is not yet fully understood. In fact, it is believed that the quark masses account for just a few percent of the baryon masses.

4. How Particles Collide According to Quantum Field Theory

So far, we have talked about electrons and quarks. They are spin-1/2 fermions. We also have photons – particles of light, which are spin-1 bosons. (The Higgs particle is a spin-0 boson). The paradigm of particle physics is that these particles interact[8] through exchange of other particles. For instance, two spin-1/2 charges interact by exchanging a spin-1 photon between them. This (Coulomb) interaction is such that two electrons repel, while an electron and a proton attracts; this is built into the theory. So electromagnetic interactions are mediated by photons or photons are the mediators of electromagnetic interactions. Since the photon itself has no electric charge, it cannot interact with itself.

This model has been extended to other interactions as well. The dominant interactions are through the exchange of spin-1 bosons. For instance, quarks exchange gluons to stay bound together within a nucleon. Hence, the spin-1 gluons are mediators of strong interactions. Gluons have no electric charge, and so photons interact only with quarks, not gluons. These interactions can be expressed as shown in *Figures* 1 and 2. Unlike photons, gluons can interact with themselves; this property makes the nature of strong interactions very different from EM interactions. These interactions can be expressed as equations, *viz.*, $ee \to ee$, $eq \to eq$, $qq \to qq$, and $gg \to gg$.

4.1 *Other Interactions*

There is one more interaction (apart from gravity which is so weak that it is ignored in particle physics) and this is the weak

[7] Another way of making colourless objects is to team up a quark of a given colour with an anti-quark of the same anti-colour, for instance, $u\bar{d}$ and $d\bar{u}$ represent the particles called pions, $\pi^{\pm}$. There are many such particles, collectively called 'mesons'. In short, baryons are three-quark states while mesons are quark–anti-quark states.

[8] So we have to replace the classical image of two colliding balls by the image of a third party mediator desperately communicating between them, causing them to scatter off in different directions.

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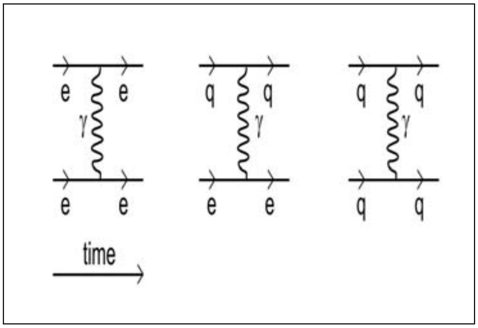

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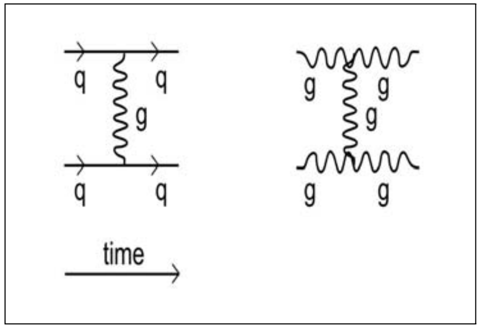

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Figure 1. Sample Feynman diagrams showing the electromagnetic processes, $ee \rightarrow ee$, $eq \rightarrow eq$, and $qq \rightarrow qq$, mediated by photons.

Figure 2. Sample Feynman diagrams showing the strong processes, $qq \rightarrow qq$ and $gg \rightarrow gg$ mediated by gluons.

interaction responsible for radioactivity. It is also responsible for the fusion processes that cause our Sun to shine, where hydrogen gets converted successively to produce the light nuclei– ${}^{2}_{1}H$, ${}^{3}_{2}He$, ${}^{7}_{4}Be$, ${}^{7}_{3}Li$, ${}^{8}_{5}B$, ${}^{8}_{4}Be$ and ${}^{4}_{2}He$ in the furnace at the star's centre [5].

These weak interactions are mediated by three gauge[9] bosons–the massive $W^{\pm}$ and the neutral Z^{0}. Their large masses are in contrast to the massless gluons and photons and make these interactions extremely short-ranged. Particles and their interactions are combined into the 'Standard Model' of particle physics [6].

[9]To understand the word gauge: any particle that is a mediator of interactions can be called the 'gauge boson', and the corresponding theory is a 'gauge theory'.

4.2 *The Particle Zoo*

As these interactions were being discovered and understood, and quantum theories were being refined, new particles were found. The first of these to be seen in cosmic ray showers by Anderson and Neddermeyer in 1936 was the 'muon', the deeply-penetrating version of an electron, about 200 times heavier than it. Anderson had noticed that there were some particles that curved differently from electrons in a magnetic field but with the same charge. He deduced that their mass had to be larger than an electron's but smaller than a proton's. In fact, they were first confused for pions which were also found in cosmic rays.

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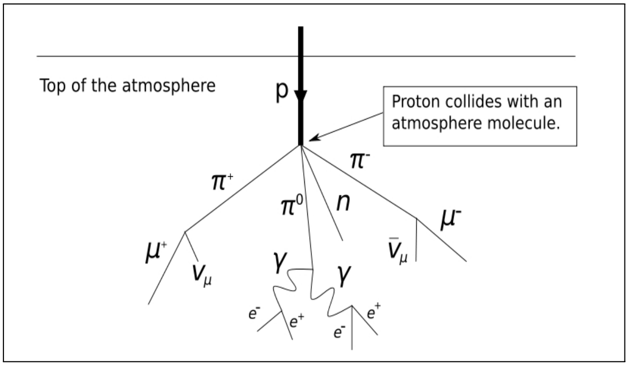

Figure 3. Schematic of cosmic rays hitting the Earth's atmosphere. (Image credit: *Wikipedia.*)

4.3 *Cosmic Rays*

Cosmic rays are just showers of very high energy particles. Most commonly (90% of the time) they are protons, and (10% of the time) light nuclei such as helium nuclei, but there can be traces of heavy nuclei as well. They are constantly bombarding the Earth and are produced outside it. In fact, the source of these particles and the reasons for their extremely high energies is a mystery[10].

[10]They are therefore very interesting areas of research, and a lot of cosmic ray research is going on in India today.

When these primary cosmic rays hit the molecules such as nitrogen in Earth's atmosphere, they copiously produce muons (*Figure* 3). They also produce a huge shower of charged particles that can be detected by ground-based detectors. These showers and muons are very energetic–from hundreds to tens of millions of MeV energy.

5. Symmetries in Nature

So what is the difference between electrons and muons? Just the mass? But we said that mass was due to interactions and so muons and electrons must have different interactions. Well, yes and no. They are so much alike that you can substitute muons for electrons to get exotic muonic atoms, although the muon soon decays (through weak interactions) into an electron. Can you substitute muons for electrons anywhere? For instance, can the muon spontaneously turn into an electron in processes such as $\mu \rightarrow e\gamma$? (The reverse $e \rightarrow \mu$ process violates energy-momentum conser-

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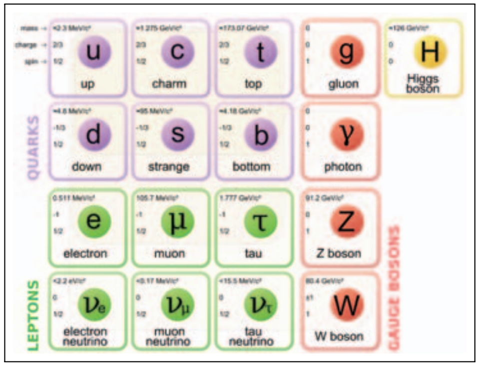

Figure 4. List of Standard Model particles. (Image credit: *Wikipedia)*

vation since electrons are lighter than muons). This decay has not been seen so far, and the experimental limit on this process is $B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$, that is, the muon decays through this process less than B fraction of the time.

It is expected that this decay does indeed take place, although the rate is very small[11]. Why? Both e and μ carry what is called a lepton number $L = 1$; they also carry individual lepton numbers or 'flavours', e: $(L_e = 1, L_\mu = 0)$ and μ: $(L_e = 0, L_\mu = 1)$. Now, L, L_e and L_μ are individually conserved in interactions. This is an example of an 'accidental symmetry'. One more 'heavy' electron, tau (τ), has been found, so there are three known lepton flavours, with their associated charge-neutral partners called neutrinos,

[11] The decay $\mu \to e\gamma$ is therefore a good place to search for new physics beyond the Standard Model of Particle Physics.

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}, \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}.$$

These are known as the three families or generations of the e, μ, τ flavour leptons. Similarly, there are three quark generations,

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}.$$

The upper and lower leptons (quarks) have charges -1 and 0 ($+2/3$ and $-1/3$) respectively) and differ by one unit (see *Figure* 4). Are there more generations? We don't know. But we will be surprised to find a solitary additional lepton without a partner neutrino, or even an additional lepton family without a quark one.

Now that we have introduced neutrinos, the dominant W-mediated

Particle	Type of Interaction: Electromagnetic	Strong	Weak
e, μ, τ	✓	×	✓
ν_e, ν_μ, ν_τ	×	×	✓
All quarks	✓	✓	✓
γ	✓	×	×
$W^\pm$	✓	×	✓
Z^0	×	×	✓

Table 1. Particles listed according to their interactions.

muon decay can be expressed as $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$. A list of particles according to the interactions they experience is given in *Table* 1.

5.1 *Weak Interactions and Flavours*

Weak interactions mediate processes such as beta decay. For instance, neutron decay is given by $n \to p\, e\, \overline{\nu}_e$, with the underlying quark process $d \to u\, e\, \overline{\nu}_e$ as shown in *Figure* 5. Here e is the beta particle emitted and $\overline{\nu}_e$ is the accompanying (anti-)neutrino (with opposite lepton number to conserve lepton number).

Unlike EM and strong interactions, charge changes in this weak interaction, as well as flavour: $d \to u$. Surprisingly it was found that the transition $s \to u$ also occurs; clearly indicating mixing between quark generations. This mixing has enormous consequences. Although the details are technical, mixing between three generations of quarks allows for something called 'CP violation'.

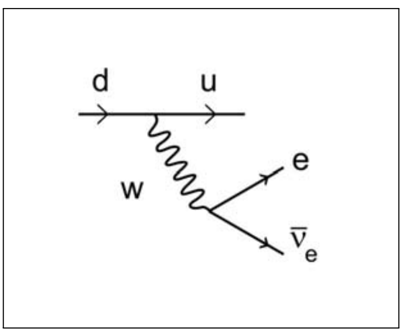

Figure 5. Feynman diagram showing the weak muon decay process $d \to ue\overline{\nu}_e$ mediated by the weak W boson.

5.2 *CP Violation in Weak Interactions: How Does it Affect Us?*

C is the 'charge conjugation' operator that converts a particle to an anti-particle and *vice-versa*. P is the 'parity operator', that changes the sign of the helicity of a particle. The helicity operator in Dirac theory, $\mathcal{H} = \sigma \cdot \hat{p}$, describes the projection of the spin operator along the particle momentum: $\mathcal{H} = +1(-1)$, for spins along (opposite) to the particle momentum. In the extreme relativistic limit, these correspond to what are called right (R) and left (L) handed chiral states[12]. Let us examine the weak decay of pions,

$$\pi^+ \to \mu^+ \nu_\mu^L \,.$$

Here L indicates that the neutrino is left-handed. If you apply the C operator to this process, it transforms to $\pi^- \to \mu^- \bar{\nu}_\mu^L$, which is not observed in Nature. Under a further P operation, we get,

$$\pi^- \to \mu^- \bar{\nu}_\mu^R \,,$$

which is indeed also observed. So our universe is (mostly) CP symmetric. As mentioned above, this is broken by quark mixing, and this CP violation has been observed in a number of processes so far. This implies that there is an asymmetry between the matter and anti-matter in this universe. If the universe did begin with a Big Bang [7], then there should have been equal amounts of matter and anti-matter today, if all interactions were CP symmetric. We know that matter dominates over anti-matter in our present universe (no anti-matter galaxies or stars have been seen so far)! Hence, CP violation has important consequences in cosmology.

Neutrinos are charge-neutral and are the most abundant particles in our universe after photons. Recent measurements have shown that there can be mixing in the neutrino sector as well, between the flavours ν_e, ν_μ and ν_τ. This means that there can be a CP violating term here just as in the quark sector. This can also contribute to the CP asymmetry, called the 'leptonic CP asymmetry'. In fact, neutrinos are considered to be a window to understanding the origin and evolution of our universe[13]. This is an open question, but this is a part of another, equally fascinating, story.

[12] The difference between chirality and helicity assumes importance when the mass of the particle cannot be ignored and accounts for processes such as pion decay.

[13] See Suman Beri, Neutrino Oscillations: New Windows to the Particle World, *Resonance*, Vol.21, No.10, pp 911–924, 2016.

6. Conclusion

This article has tried to give a flavour of particle physics – the zoo of particles and their interactions and how this defines the very universe we live in. Ultimately, the three interactions – electromagnetic, strong and weak, must be reconciled with gravity to completely understand the world we live in. In recent times, it has been found that this 'known' universe with these particles and interactions comprises just 5% of the total mass-energy density of the universe. The dominant contributor at 72% is an exotic form of energy that exerts a negative pressure, called 'dark energy'. Another 23% is composed of 'dark matter'. Its existence is inferred indirectly from its gravitational interactions but the nature of this matter is totally unknown [8]. Exciting times still lie ahead.

Neutrinos are charge-neutral and are the most abundant particles in our universe after photons. Recent measurements have shown that there can be mixing in the neutrino sector as well, between different flavours.

Acknowledgement

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Suggested Reading

[1] G Parisi, Popular article on Brownian motion for the centenary celebrations of Einstein's discoveries, *Nature*, Vol.433, p.221, 2005.

[2] A nice explanation and animation of Rutherford's famous experiment can be found at: https://micro.magnet.fsu.edu/electromag/java/rutherford/

[3] The text of Aston's Nobel prize speech can be found at: https://www.nobelprize.org/nobel_prizes/chemistry/laureates/1922/aston-lecture.pdf; the last paragraph is particularly prophetic.

[4] *The Feynman Lectures on Physics, Volume II*; The relevant chapter can be found on-line at: http://www.feynmanlectures.caltech.edu/II_28.html

[5] Popular articles by John Bahcall on "How the Sun Shines" and the "Solar Neutrino Problem", see: http://www.sns.ias.edu/ jnb/

[6] To get a feeling for the important issues in particle physics, look at The Table of Contents of the "Particle Data Group" Review at: http://pdg.lbl.gov/2016/reviews/contents_sports.html

[7] A nice and short review by NASA in: https://science.nasa.gov/astrophysics/focus-areas/what-powered-the-big-bang

[8] The Particle Adventure– www.particleadventure.org, an award winning site on particles and their interactions; highly recommended for the interested.

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