The Forces of Nature

Physicists are confident that there are four fundamental forces of Nature – the gravitational force, the electromagnetic force, the strong force and the weak force. Gravity binds galaxies and stars together and is largely responsible for the way the Universe is; the electromagnetic force binds atoms together and is therefore responsible for pretty well all of Chemistry; the strong force binds nuclei together and provides us with the mechanism by which the stars shine and the weak force is, and I quote from virtually every book that has been written on the subject, 'responsible for beta decay'. It is immediately obvious that the so-called 'weak force' is the Cinderella in the pack. Nobody knows what it is *for*. Not, of course, that any physical process need be *for* anything – but still, it is difficult to see where it fits into the overall picture. Without gravity, electromagnetism and the strong force, the universe would be a very different place and life as we know it would not exist but it has been argued[1] that a universe without the weak force could still contain stars, galaxies, Chemistry and, perhaps, even life.

The Coupling Constants

Each of the four forces of nature are characterized by a dimensionless number called the coupling constant. One of the ways of defining this number is in terms of the ratio of the energy of a typical system divided by the energy of a photon of the same size. For example, the electrostatic energy of two elementary charges separated by a distance *r* is:

$$U_e = \frac{e^2}{4\pi\epsilon_0 r} \tag{1}$$

and the energy of a photon of wavelength *λ* is

$$U_p = \frac{hc}{\lambda} \tag{2}$$

If we assume that the wavelength *λ* is equal to 2πr, the ratio of these quantities is

$$\alpha_e = \frac{U_e}{U_p} = \frac{e^2}{2\epsilon_0 hc} = 7.3\times 10^{-3} = \frac{1}{137} \tag{3}$$

For a time this number (which is called the Fine Structure Constant) was given almost mystical significance by Sir Arthur Eddington but it is now regarded as just one of the many constants which define the universe we live in.

Now lets consider gravity. The gravitational potential energy of two point masses *m* separated by a distance *r* is

$$U_g = \frac{Gm^2}{r} \tag{4}$$

which gives us an expression for the gravitational coupling constant of

$$U_g = \frac{2\pi G\ m^2}{hc} \tag{5}$$

The problem here is that, while we have a natural unit of charge, there is no obvious natural unit of mass. The usual mass to use is the mass of a proton which gives us a value of

$$\alpha_g = 5.9\times 10^{-39} \tag{6}$$

This number is often compared with the Fine Structure Constant and is used to point out how very much weaker gravity is than electromagnetism. I always think this is a bit unfair on gravity.

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1 See https://arxiv.org/pdf/hep-ph/0604027.pdf Harnik, Kribs and Perez A Universe Without Weak Interactions

After all, there is nothing special about the mass of a proton. Why not be even more unfair and use the mass of an electron? There is, however, one mass which *is* special and that is the Planck mass one of whose definitions is equal to

$$m_{planck} = \frac{1}{2\pi}\sqrt{\frac{hc}{4G}} = 4.3\times10^{-9}\,\text{kg} \quad ` \tag{7}$$

Putting this expression into equation (5) give us

$$\alpha_g = \frac{2\pi G}{hc}\times\frac{1}{4\pi^2}\frac{hc}{4G} = \frac{1}{8\pi} \tag{8}$$

which gives us a bit of a problem. You see, gravity is supposed to be a lot weaker than the electromagnetic force. But if my calculations are valid, its coupling constant is actually larger. The truth is that you really can't compare gravity with electromagnetism because we have completely different theories to explain them. Perhaps when we are in possession of a quantum theory of gravity, we shall have a better basis for comparison. Until that time, I think we should stop talking about gravity as if is was an incredibly weak force. Just try lifting a large stone if you don't agree with me!

When it comes to calculating a coupling constant for the weak force, we can use an expression similar to that of equation (1) whereby (for small values of r at any rate)

$$U_e = \frac{g_f^2}{4\pi r} \tag{9}$$

where $g_f{}^2$ plays the role of e^2 / ε_0. Experiment shows that $g_f{}^2$ has the value 4.0×10^{-30} J m which gives us a value for the coupling constant of the weak interaction as

$$\alpha_w = \frac{g_f^2}{2hc} = 1.0\times10^{-5} \tag{10}$$

Likewise, for the strong force between a neutron and a pion we have

$$U_e = \frac{g_{N\pi}^2}{4\pi r} \tag{11}$$

where $g_{N\pi}{}^2$ has the value 5.8×10^{-24} J m which gives us a value for the coupling constant of the strong interaction as

$$\alpha_w = \frac{g_{N\pi}^2}{2hc} = 14.6 \tag{12}$$

The range of the four forces

It is well known that the range of the electromagnetic and gravitational forces is infinite and the force falls off as the square of the distance. From a quantum mechanical perspective, the infinite range is due to the fact that the medium by which the force is propagated, namely the photon and the graviton respectively, have zero rest mass.

Now the weak force is mediated by the W and Z bosons which have a rest mass/energy E_Z of approximately 90 Gev or 90 times the mass of a proton. During an weak interaction, one of these particles has to be created temporarily. According the Heisenberg's uncertainty principle, this puts a time limit on the duration which it can survive and therefore the range of the force it can transmit. This range will be

$$r_{weak} \approx \frac{hc}{E_Z} = \frac{hc}{90\times10^9 e} = 1.4\times10^{-17}\,\text{m} \tag{13}$$

which is considerably smaller than the radius of an atomic nucleus.

The strong force is mediated by pions which have a rest mass/energy of about 135 Mev.

Doing a similar calculation results in

$$r_{strong} \approx \frac{hc}{E_Z} = \frac{hc}{135\times10^6 e} = 10^{-14}\,\mathrm{m} \tag{14}$$

Both of the above calculations should be taken with a large dose of salt, however as the situation is far more complex than this. For example, both the weak and the strong forces fall off exponentially so, in theory, their range is theoretically infinite too; it just becomes vanishingly small after a certain distance.

Which particles feel which force?

All particles feel the gravitational force, even the photon which has zero rest mass, because all particles have energy and, according to General Relativity, energy and mass are equivalent.

Only *charged* particles like the proton and the electron feel the electromagnetic force.

Strictly speaking, only *quarks* feel the strong force but since quarks are never found on their own it is the particles which are made of quarks such as protons, neutrons and more exotic things like pions which actually feel the strong force. Quarks possess an intrinsic property called colour charge which is analogous to electric charge – the main difference being that there are actually six types of colour charge, not just positive and negative versions.

Once again, the weak force is the odd one out. There is no such thing as the 'weak charge' and really there isn't any mileage in talking about a 'weak force' at all as there are no circumstances in which it makes sense to add or subtract this so-called force from one of the other forces.

The modern view of the three quantum forces (i.e. all of them except gravity) is that they come about because of the exchange of virtual particles. It is envisaged that, as two charged particles approach each other, the exchange of virtual photons between them causes a recoil effect in the same way that you might imagine a British and a French warship exchanging cannon shot during a battle might experience a repulsive force between them due to the recoil of their own guns and the weight of iron hitting them. (Analogies like this can, however, lead to serious misunderstandings. It is, for example, pointless to try to explain how charges of opposite sign can *attract* each other by this method. Tricks like talking about 'negative momentum' or particles moving 'backwards in time' are just tricks and will not wash. The truth is that as an electron sails past a proton, their wave functions interact in such a way as to produce the change in momentum which we associate with an attractive force. And if you want to know how this is done you have to bite the bullet and learn some quantum mechanics.) Similarly two quarks exert a force on each other by exchanging virtual particles called gluons. In fact it would be much better to abandon the use of the word force and simply say that there is an *interaction* between the two particles.

The most important 'weak' interaction is the decay of a neutron. Neutrons can exists on their own but, surprisingly, they are not stable. With a half life of about 10 minutes, an isolated neutron will turn into a proton emitting an electron and an anti-neutrino. The same process can occur inside a nucleus but with half lives which vary from microseconds to millions of years. The problem was not so much explaining why this reaction occurred but why it sometimes took so long. The problem was solved when it was realised that the reaction was not quite as simple as had been thought but that it involved an intermediate stage in which another particle – in this case the W^- boson – was created which subsequently decays into an electron and an anti-neutrino. But this particle is never observed in bubble chamber photographs of neutron decay because it is a very massive particle and therefore cannot last very long in its virtual form. This also explains why neutron decay takes so long because the more massive a virtual particle is, the smaller the probability of creating it in a given time.

In 1983 the W and Z bosons were created artificially in the SPS collider at CERN and have since been observed many times and their masses measured accurately but it is worth noting that in reality, only the decay products of these particles have actually been detected. The half life of these particles is so short that they cannot travel more that about 10^{-17} m before they decay so there is no photograph which shows a W particle created *here* and decaying *there*; what we actually see is a so-called *resonance* – a sudden peak in events of a certain type at a certain energy.

The weak interaction

So where does the weak interaction fit in to the grand scheme of things? It doesn't hold atoms together and it doesn't hold nuclei together. So what is it *for*? What would the universe look like if there was no weak interaction?

The most obvious consequence is that there would be no beta decay. There would still be radioactive isotopes but they would decay either by alpha decay or by shedding protons or neutrons. Apart from reducing the amount of heat generated in the interior of planets, this would not cause any material change in either physics, chemistry or biology in later epochs.

There is, however, one epoch in which the weak interaction does play a crucial role. Immediately after the big bang the universe was a seething mass of pure energy in the form of photons, quarks and gluons. Within a few microseconds, the quarks will have teamed up into pairs (e.g. mesons) or triplets (e.g. neutrons and protons). (For some reason, as yet unknown, far more matter was produced in this period than anti-matter.) It is now that the weak interaction comes into its own because it is through this mechanism that a neutron colliding with a positron can turn into a proton (and an anti-neutrino); similarly a proton colliding with an electron can turn into a neutron (and a neutrino). (These are all versions of the beta decay process mentioned earlier.) At first the ratio of protons to neutrons is 1:1 but owing to the fact that the proton is slightly less massive than the neutron, the neutrons decay into protons and gradually the ratio rises to about 7:1. Within a few minutes, all the remaining free neutrons have been gobbled up by the available protons to form the ultra-stable Helium nucleus which contains 2 protons and 2 neutrons. When all the neutrons have either decayed into protons or combined to form Helium nuclei there will be approximately 12 single protons to every Helium nucleus. Since the Helium nucleus has 4 times the mass of a proton, the percentage of Helium by mass is equal to 25% – a figure which matches very well with the observed ratio of Hydrogen to Helium in interstellar space.

If the weak interaction did not exist, we might speculate that neutrons and protons would be created in equal numbers. If this was the case, all the neutrons and protons would pair up into Helium and there would be no Hydrogen at all! But this does not necessarily mean that there would be no stars, no planets and no life. Stars generate heat not only from the fusion of Hydrogen into Helium but also from the fusion of Helium into heavier elements up to Iron. It is probable that a universe which started with little or no Hydrogen would look rather different from ours but if one is permitted to fiddle with other parameters such as the Gravitational constant etc. it is possible to create plausible 'weakless' universes with stars, galaxies, chemistry, planets and, who knows, even life.

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