

Particle Physics

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1 Introduction

This course is about the basics of particle physics, lectured by .

- 1897, J.J. Thompson discovered electron
- 1919, proton is discovered by Rutherford
- 1932, neutron discovered by Chadwick
- 1928, there was a ickle bit of a problem, Dirac looked at $E^2 = p^2c^2 + m_0^2c^4$, everything is in units of energy¹ in this equation. $E = \pm\sqrt{p^2 + m^2}$ what is it with the negative energy? There are two ways of explaining this Feynman's way and Dirac's way.

Dirac's "Hole" explanation This idea was declared rubbish by Pauli.

Normally ("vacuum") all the negative energy states are full, therefore no positive energy electron can go down into one of the states with negative energy (Pauli exclusion principle). However you are allowed to go from negative energy to positive energy, this means an electron absorbs enough energy ($\geq 2mc^2$) to make the transition. If this transition happens you are left with a "hole" in the negative energy levels.

¹as particle physics goes we use $c=1=\hbar$. So previous equation becomes $E^2 = p^2 + m^2$.

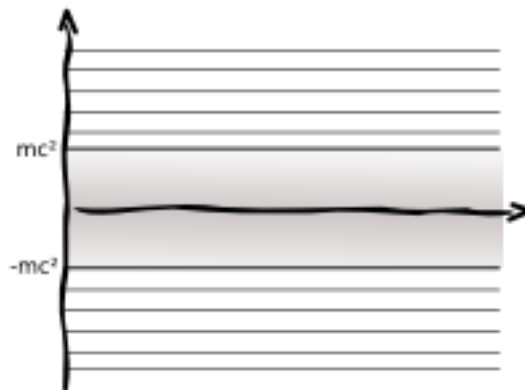


Figure 1: Figure1

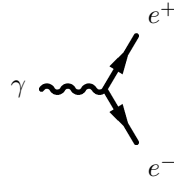


Figure 2: This is a Feynman diagram of so called “pair production”. One electron and one positron is created.

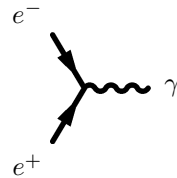


Figure 3: When an electron and positron meet they annihilate and a photon is produced.

This hole can now be filled (or destroyed) by a positive energy electron dropping into that state. The Feynman diagram in Fig 2 shows this process.

In Fig. 3 an electron and a positron annihilate into a photon.

Feynman’s explanation – Fred’s simplified version Starts with a wave function with positive energy (E^+)

$$\psi(x, t) = \exp(i(kx - \omega t)) = \exp\left(\frac{i}{\hbar}(px - E^+t)\right)$$

For negative energy (E^-) this is

$$\psi(x, t) = \exp\left(\frac{i}{\hbar}(px - E^-t)\right) = \exp\left(\frac{i}{\hbar}(px - |E^-|(-t))\right)$$

so this is basically a particle with positive energy moving backwards in time.

Consider a charged particle, e.g. electron e^- moving forwards in time in a magnetic field B .

$$F \propto (-e)v \times B$$

for an electron moving backwards in time

$$F \propto (-e)\frac{dx}{d(-t)} \times B \propto (+e)\frac{dx}{dt} \times B$$

so its just a particle with opposite charge (in case of electron it has charge $+e$) moving forward in time. For every particle with positive energy E^+ there exists a particle of negative charge E^- . This is true even if there is no magnetic field, this argument applies for all arithmetical additive quantum numbers. So there must exist a particle which is exactly opposite in all quantum numbers for every particle, e.g. electron has positron.

1932, Anderson uses cloud chamber with cosmic rays Look at fig4

The amount of ionization (leads to droplets) suggests that this was an electron like particle. Smaller radius of curvature below the lead \Rightarrow lower momentum. From Flemming’s left hand rule and direction of travel we can work out this is like an electron but with positive charge.

1955, Chamberlain et builds the BETATRON This can accelerate protons. Chamberlain was looking for anti protons \bar{p} . Process goes like this $p + p \rightarrow \bar{p} + p + p + p$ (a proton beam hits a target). All these protons are produced to conserve charge.

Neutron β decay A β particle is nothing else than a electron. They decay with a lifetime of about 900s to a p and e^- .

$$n \rightarrow pe^-$$

This has a problem though, the energy of the neutron $>$ combined energy of proton and electron. To make things worse angular momentum was missing to. All particles involved are fermions, i.e. half spin particles, $\frac{1}{2} \neq \frac{1}{2} + \frac{1}{2}$. It gets even worse as momentum is wrong too. Consider the fact of neutron decaying when it is at rest, this would require that proton and electron have equal and opposite momenta. As the neutron has a well defined mass which implies that the magnitude of this momentum is very well defined and unique. So we would expect a very clear peak in a histogram of the energy/momentum of the electron. This was not the case. Electron energy/momentum is a distribution and not a sharp peak.

1934, Fermi postulates the neutrino Neutrino is a particle with zero or very little mass, zero electric charge and must have half spin. So reaction becomes

$$n \rightarrow pe^-\nu$$

They only interact by weak interaction, so very very difficult to actually observe. If 10^{10} neutrinos ν travel through the earth $10^{10} - 1$ will come out. Pauli thought this was rubbish and wagered a whole crate of champagne (“Nicht mal falsch”).

1959, Reines and Cowan detected a huge bunch of neutrinos with neutrons from nuclear reactors. $n \rightarrow pe^-\bar{\nu}$ and use the neutrinos to bang them into protons $\bar{\nu}p \rightarrow ne^+$, the positron is easy to detect as it decays instantly.

1935, Yukawa proposes the strong nuclear force which binds e.g. protons in the nucleus. Due to the exchange of “Nuclear radiation”. Equivalent to the exchange of photons in EM interaction. From uncertainty principle you get the range of strong interaction to be $\approx 10^{-15}$. The mass of exchange particle was expected to be about $150MeV$.

1937, the Muon (μ^\pm) discovered, with right mass but wrong properties. They sailed through the atmosphere but did not interact with it, if you are the particle responsible for strong interaction you better interact with stuff by it. After ten years they finally figured out that it was certainly not what they were looking for.

1947, the pion($\pi^{\pm 0}$) is discovered, it had the right mass(140MeV) and had the right properties, either decayed or interacted in the upper atmosphere. This is also called the Pi meson, but most people call it the pion. Insert figure 4-10-1. First lifetime measurements of π were made on a film in a cocoa tin in the swiss alps, it decays as $\pi^{\pm} \rightarrow \mu^{\pm} \dots$. In rest frame of π , momentum of muon was always same \Rightarrow must be a two body decay(each one with exactly equal and opposite momentum). By energy conservation of the mass of missing particle must be ≈ 0 , either γ or ν . It was not a photon so it had to be a neutrino. The other kind of pion π^0 decays as follows: $\pi^0 \rightarrow 2\gamma$. Its mean life time $\tau_{\pi^0} = 10^{-16} s$.

The decay of the muon goes as $\mu^{\pm} \rightarrow e^{\pm} + \text{not seen}$. In rest frame of μ energy of e is not fixed, so there had to be at least two unseen particles. No missing mass though so that it can only be photon or neutrino. It is $\mu^{\pm} \rightarrow e^{\pm} \nu \bar{\nu}$.

Problems there is a set of problems generated by these particles.

1. Lifetimes, going to be solved by interactions
2. Size, solved by the quark model

We will deal with problem two first.

Fred's very basic version of the quark model for hadrons

Quarks are constituents of hadrons. If a particle has a size then there has to be some kind of substructure in it. Known properties of hadrons, proton and neutron have spin $\frac{1}{2}$ (fermions), called Baryons. Pions($\pi^{\pm 0}$) have spin zero(bosons), called Mesons. Hadrons come with integral(p, π^{\pm}) or zero(n, π^0) electric charge. Quarks were introduced in 1964 by Gell-Mann(Quarks) and Zweig(Aces).

1. Baryons have $\frac{1}{2}$ spin \Rightarrow quarks must have $\frac{1}{2}$ integral spin(fermions), could be quarter, eighth etc, but we choose the simplest way of doing it.
2. Baryons must be made of an *odd* number of quarks, because if we had even number there would not be a spin left over. As one quark making up one baryon does not add anything to our understanding, so we go with three quarks per baryon.
3. Mesons have integral spin, therefore mesons must be made of *even* number of quarks. Again the simplest way to do this is one meson has two quarks.
4. Baryons have integral or zero electric charge. Quarks have electric charge in units of thirds of electron.
5. Mesons have integral or zero electric charge. Mesons must have two quarks in combination

This leads to (initially) three types of quarks, up, down and strange.

Here you should go and look at a table of how Baryons and Mesons are made up of these basic quarks. Now to the anti particles of the proton, neutron, π^{\pm}, π^0 . For proton and neutron just inverse all quarks involved to get the anti particle(protons are uud so will go to $\bar{u}\bar{u}\bar{d}$). The π^0 is special because it is a

	up	down	strange
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
electric charge	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$

Table 1: This is a table of the basic properties of the basic three quarks. The antiparticles have same spin but exactly opposite electric charge, so the sum of charge is zero.

superposition of these two ($u\bar{u} + d\bar{d}$) states. As $\bar{\pi}^+ = \pi^-$ they are each others anti particles. Even more consuming that the $\bar{\pi}^0$ is the anti particle for the π^0 . So it is its own anti particle.

Interactions

What kind of interactions do we have between all these quarks?

Strong Binds quarks in hadrons(stronger then coulomb repulsion)

Electromagnetic Interactions between all charged particles

Weak Interactions between all particles

Gravity This is so weak that we will not talk about it in this course

All these interactions(sans gravity) can be explained within the framework of *Grand Unified Theory*. If we include gravity this becomes *Theory of Everything*. Which interaction to choose if multiple ones are available? A general rule of thumb is to choose the strongest one. Consider the proton, it can interact via Strong as it has quarks, it is charged so it can also interact via electromagnetic, it is a particle so it could use weak interaction and finally it has mass so gravity could be in charge. Following our rule of thumb the proton will interact via the strong force. Sometimes it can not be the strongest available force, this is due to conservation laws as we will see later.

Electromagnetic interaction will be considered first. Insert figure 5-10-1. If the electron would only sit there it would not notice a another electron sitting close to it, they would not interact. We explain this with the help of a “virtual photon”. This virtual photon can not be detected and does not need to obey conservation of energy and momentum. As the virtual photon has an energy ΔE it can only be “gone” for a time Δt give by $\Delta E \Delta t \approx \hbar$. Sometimes the virtual photon will not return to its home-base but go to another electron. This requires a virtual photon from that electron to travel to the original electron within time Δt in order to satisfy Heisenberg’s uncertainty. As the exchange of photons means we are exchanging momentum the electrons will start moving.

Force per photon is given by $\frac{P}{t} = \frac{pc}{t} \approx \frac{\hbar c}{r^2}$. The number of photons emitted per absorbed between 2 electrons $\propto e^2$.

All interactions mediated (carried) by virtual bosons, particular boson associated with particular interaction, e.g. electromagnetic:

Source electric charge(e from charge on electron)

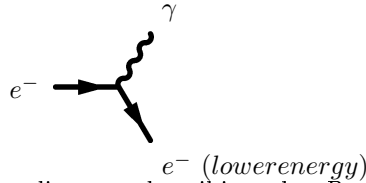


Figure 4: This is a Feynman diagram describing the *Bremsstrahlung* phenomenon. We should really also have a recoiling nucleus.

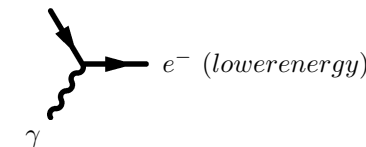


Figure 5: Photoelectric effect as a Feynman diagram, again there should be a nucleus visible as one needs an atom to liberate the electron.

Propagator virtual photon, determines range

Strength characterized by “coupling constant”, α in cross-section ($\sqrt{\alpha}$ in amplitude), $\alpha \sim e^2$. α is dimensionless and given by $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} = \frac{1}{137}$, also known as “fine structure constant”.

Look at Bremsstrahlung as an example of this interaction. (Insert Feynman diagram 11-10-1)

Figure 6 shows a Feynman diagram of two electrons interacting via virtual photon.

In figure 7 an electron (e^-) and a positron (e^+) annihilate and are recreated. The created particles are different particles to the two incoming ones. This looks almost like two charge particles interacting via EM interaction but is different.

All processes with only EM interaction (vertices) are fully described by QED. This theory has been tested & works (to high precision) over $10^9 m \rightarrow \leq 10^{-19}$. QED assumes point like sources for electrons, fact that that QED works down to $\leq 10^{-19} m$ implies that diameter of electron is smaller than this.

Strong Interaction uses the *Gluon* as propagator between *Colour* charges (eg. in quarks). With a coupling constant $\alpha_S \approx 100 \times \alpha_{EM}$. Some call this a “running constant”.

Gluons only interact with colour charge which is restricted to quarks (which have colour) and gluons. The photon does not have electric charge, however the gluon does have colour charge. A photon can not change the charge or type of particle, whereas the gluon does change colour of particle but not the type of particle (up quark stays up quark).

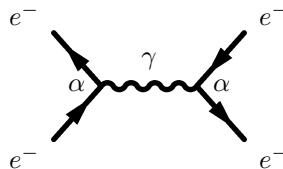


Figure 6: Feynman diagram showing how two charge particles (i.e. electrons) interact via a virtual photon. The cross-section of this interaction is $\sim \alpha^2 \sim e^4$ as expected from Rutherford scattering.

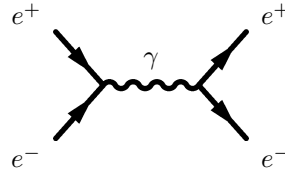


Figure 7: This shows annihilation followed by pair production. It is important to note that the particles on the left-hand side are different to the ones on the right. The photon is virtual as in EM interaction.

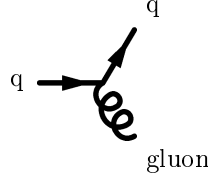


Figure 8: This shows a process equivalent to the one shown in figure 4. Only this time with quarks, at the interaction vertex we have a cross-section α_S .

Weak interaction Uses the W^\pm, Z^0 particles as propagators. It acts on all particles, therefore it has to couple to both leptons and quarks (unlike strong interaction which only couples to quarks). For the moment we will just assume that the mass of the W&Z are very large. Later we will come back as to why this is so. As a result of this the range of virtual particles is small. Why is this so? The time a virtual particle can “go missing” is given by $\Delta E \Delta t \sim \hbar$. As ΔE depends on the rest mass, Δt is smaller for heavier particles, Δt determines how far it can travel. Virtual particles travel at speed of light.

As the two propagator particles have different charge we will treat them separately.

The W^\pm We will now play around with more Feynman diagrams. Figure 10 shows process of an electron going backwards in time. Don't worry about this to much as we can rotate the frame to get W^- producing electron&neutrino. We can combine the two diagrams in figure 10 to get diagram shown in figure 11.

If we add two quarks over the down quark, they are spectator quarks, i.e. they don't interact with anything. However two down and one up quark coming in are a neutron and out come two up and a down, a proton. So we now have a Feynman diagram describing how neutrons decay to protons. This is a well known process called β -decay.

The W^- particle in this decay has to be virtual because there is not enough energy to produce a W with rest mass of 80GeV, so we can only produce a virtual particle. Virtual particles are just like real ones except you can not detect them.

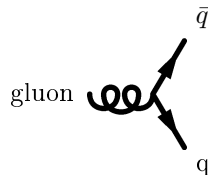


Figure 9: This is the quark equivalent to pair production (see figure 2). At the interaction vertex we have again α_S .

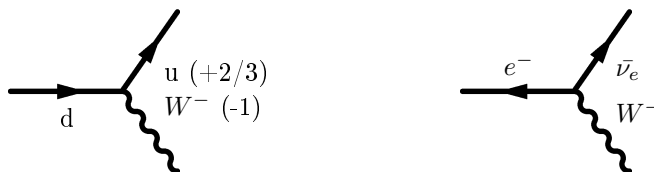


Figure 10: An example of how quark flavor changes by radiating a W^- . Flavor changes from down to up. Second diagram is an example of how lepton type changes by radiating a W^- , goes from a electron traveling back in time(essentially a positron) to electron neutrino. This could easily be rotated so that the W^- produces electron and neutrino.

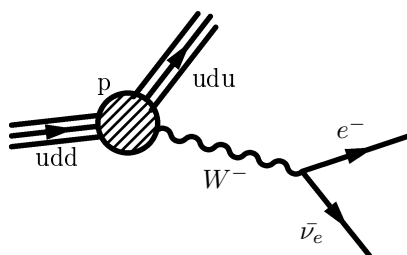


Figure 11: This shows a neutron(quarks udd) decaying to a proton(quarks udu). This is basically a combination of figure 10 with two spectator quarks added to make up a neutron.

The very small energy excess(Q value) explains the very slow decay rate of $n \rightarrow e^- \bar{\nu}_e$ process.

The Z^0 This must couple to both leptons and quarks. See figure 12 for a neutrino radiating a Z^0 . The emission of a Z^0 does not change the flavor of a quark. A combination of -5&-6 give proton-neutron scattering, like electron-proton scattering.

Due to the fact that α_{EM} is much bigger than α_W it dominates over the weak interaction. This is only true for “long distances”, on short ranges the weak interaction is just like EM interaction. At energies of $\sim 100\text{GeV}$ distances probed are of order $\sim 10^{-18}\text{m}$, which is in range for the weak interaction, $\alpha_W = \alpha_{EM}$. The energy is also close to the rest mass of the W & Z particles, so they can actually be created.



Figure 12: First diagram shows a neutrino radiating a Z^0 . Second diagram an up quark radiating a Z^0 and staying an up quark. As the Z^0 is its own anti-particle \bar{Z}^0 this could equally well be radiating a \bar{Z}^0 .

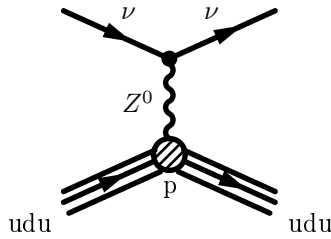


Figure 13: Neutrino-proton scattering via a Z^0 boson. This is a combination of figure 12 with two spectator quarks added to make up the proton.

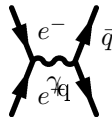


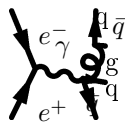
Figure 14: electron anti electron annihilate If the bottom \bar{q} is a \bar{d} quark and we have a u quark(together this is a π^+) then we get a π^- (made of d and \bar{u}).

Gravity uses the Graviton as propagator. Which has mass zero, hence range is infinity. It has to have integer spin, it turns out to have spin 2 which is rather strange. It has not been found yet! They tried to detect it with two big metal cylinders with strain gauges on them. If gravitons from outer space come and interact with the cylinder you will see coincident in the interactions. This experiment has now been abandoned. Remember the article about gravity waves? They are going to launch satellites to get outside of the earth to lower the background noise.

Gluon do we have real gluons or only virtual ones? In 1979 at PETRA (Hamburg) $e^-e^+ \rightarrow hadrons$.

Actually we get a jet of hadrons as we have multiple $q\bar{q}$ production. However gluon interactions shown in figure gluon strahlung, gluon quark anti quark. Together these are

W^\pm couples to both quarks & leptons. eg $d \rightarrow uW^-$ and $e^+ \rightarrow \bar{\nu}_e W^+$. Shuffle these around to get $\bar{u}d \rightarrow W^-$ and $W^- \rightarrow e^- \bar{\nu}_e$. We can stick these two together to “discover” the real W. To do this we use a $p\bar{p}$ collider (1983 at CERN). See diagram 16-10-1, showing W This experiment has a problem, how do we detect a $\bar{\nu}_e$ anti electron neutrino? We use missing energy technique. Measure invariant mass of $(e^-, \bar{\nu}_e)$ pair. If you then plot number of events with certain invariant mass vs invariant mass. If there is nothing special about the neutrino we will see a peak at the mass of the real W particle, diagram 16-10-2. However we do see a peak for the combine mass of electron and neutrino which means it has to be the decay product of the W.



This is a three jet event, this is evidence of real gluon production.

Z^0 also couples to both quarks and leptons. $\bar{u}u \rightarrow Z^0$, look at diagram 16-10-3. Again we look at the invariant mass of $\mu^+\mu^-$ pair, which gives a well defined peak at 91GeV, which is evidence for a real Z^0 .

Both the W & Z were predicted by Glashow, Salam and Weinberg, so at CERN they built the $p\bar{p}$ collider at CERN by Van der Meer and the the experimenter leader was Rubbia. All of these won the Nobel prize for this. Then did e^+e^- annihilation for Z^0 production were the energy of incoming e^+ and e^- to be exactly the rest mass of Z^0 . This produces a Z^0 with no kinetic energy, so its at rest and follows energy and momentum conservation.

Conservation laws

16.11.2006

Noether's theorem states: Invariance under some transformation leads to conservation of some related quantity. We will do two sections, "old" and "new" conservation laws.

Old Conservation laws include angular momentum, which says that invariance under spatial rotation leads to conservation of angular momentum L . In general $\vec{J} = \vec{L} + \vec{S}$, orbital plus intrinsic spin. Start with following assumptions, $s_{p,n} = \frac{1}{2}$, $s_{e^-} = \frac{1}{2}$ and $s_\gamma = 1$. We should also be aware that spin of a particle equals the spin of its anti-particle. Arithmetically additive quantum numbers are reversed between particle & anti-particle. We know β -decay, $n \rightarrow pe^- \bar{\nu}_e$, this implies that $s_{\bar{\nu}} = \frac{1}{2}$ for angular momentum to be conserved. Neutrinos are fermions with half integer spin.

Very rare π decay (0.01%) $\pi^+ \rightarrow e^+ \nu_e$ and $\pi^- \rightarrow e^- \bar{\nu}_e$, this implies that $s_{\pi^\pm} = 1$. This implies that Pions are bosons.

μ very similar to e so therefore spin $\mu = \frac{1}{2}$. This "similarity" is confirmed by measurement of gyromagnetic ratios).

Common π decay, $\pi^+ \rightarrow \mu^+ \nu_\mu$ and $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$. This leads to conclusion that ν_μ and $\bar{\nu}_\mu$ have half integer spin, therefore are fermions.

New conservation laws Leptons $n \rightarrow pe^- \bar{\nu}_e$ after which we can do $\bar{\nu}_e p \rightarrow ne^+$ or equally $\bar{\nu}_e p \rightarrow n\mu^+$, but latter does never happen.

Also have $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ which can be followed by $\nu_\mu p \rightarrow \mu^+ \dots$ or $\nu_\mu p \rightarrow e^+ \dots$, again latter thing never happens. From this we deduce that there have to be two kinds of neutrinos ν_μ and ν_e (and their anti-particles). In 1977 the τ was discovered which lead to the idea there had to be a tau-neutrino too μ_τ .

$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ and $\mu^+ \rightarrow e^+ \gamma$, this would both happen if the neutrino is like an electron but more massive, latter does not happen so they have to be fundamentally different $\nu \neq p \neq \tau$ type particles.

We implement this in our framework as following, e-type particles given electron lepton number = $L_e = \pm 1$, μ -type particles given muon lepton number = $L_\mu = \pm 1$ and τ -type particles given tau lepton number = $L_\tau = \pm 1$. All non-leptons, all hadrons and all force bosons have zero lepton number. As they are arithmetically additive, they are reversed for equivalent anti-particles.

L_e, L_μ, L_τ are all separately conserved (but watch this space for neutrino oscillations).

	L_e	L_μ	L_τ
e^-	1	0	0
e^+	-1	0	0
ν_e	1	0	0
$\bar{\nu}_e$	-1	0	0

Table 2: Lepton number convention.

Particle	Mass(MeV)	Decay Mode	τ	
γ	0	Stable		
ν_e ν_μ ν_τ	~ 0	Stable		No lighter part
e^-	0.5	Stable		No lighter p
μ^-	100	$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$	2×10^{-6} ,	Need $\nu_e \nu_\mu$ to
π^+	140	$\pi^+ \rightarrow \mu^+ \nu_\mu$	3×10^{-8}	Need
π^0	140	$\pi^0 \rightarrow 2\gamma$	10^{-16}	No conservation law forbids this decay, but can not
p	1000	Stable	$> 10^{33}$ years	

Table 3: Summary of particle properties, add last line neutron: $n, n \rightarrow p e^- \bar{\nu}_e$, 900, Needs proton to conserve B, needs e to conserve Q, needs neutrino to conserve L_e number

23.11.2006

Baryons We know from experiments $pp \rightarrow pp\pi^0$, we might expect a similar processes like $pp \rightarrow p\pi^+$ and $pp \rightarrow \pi^+\pi^+$ and $p\bar{p} \rightarrow \pi^+\pi^-$ and $p\bar{p} \rightarrow p\pi^-$ and $p\bar{p} \rightarrow pp\pi^-\pi^-$ and $p \rightarrow e^+\nu_e$ but they do not. Only one that also works is $pp \rightarrow \pi^+\pi^-$. This leads us to a new conservation law, conservation of baryons. We assign the quantity B which is $B = +1$ for baryons, $B = -1$ for anti-baryons and $B = 0$ for mesons and all none hadronic particles. For quarks we have $B = +\frac{1}{3}$ and anti-quarks $B = -\frac{1}{3}$. B is conserved in all interactions&decays, but watch out for GUTS. B is arithmetically additive quantum number.

Mesons for example π , we know from experiments that $\pi^0 \rightarrow 2\gamma$, we can immediately deduce that mesons are not conserved.

Strangeness

It was discovered ins 1947 by Rochester&Butter(in Manchester) by using a cloud chamber to detect cosmic rays. They get tracks appearing from no where, a neutral particle decaying into two charged particles. One can measure its lifetime by measuring its flight path before the decay. Decay events of type: $K^0 \rightarrow \pi^+\pi^-$, this is what was actually observed by them. We could also have $\Lambda^0 \rightarrow p\pi^-$ but did not.

This was the last “non accelerator” particle physics experiment, after this we discovered lots of new particles. All these new particles have the property of *strangeness*. K^0, Λ^0 (and others) produced with high probability by Strong interactions (in lead sheet). K now could satisfy all thus far known quantum numbers and would be expected to decay by the strong interaction, $K^0 \rightarrow \pi^+\pi^-$

Figure 15: Quark flow diagram. 23-10-1. The $s\bar{s}$ pair is produced by strong interaction. Both W^\pm are particles that interact by weak interaction(slow), this explains decay time.

with $\tau \approx 10^{-23}s$. What we find is though $\tau_{K^0} \approx 10^{-8} - 10^{-10}s$, the fact that there is a range of times available should no bother us now, more worrying that these are times in the range of weak interaction not strong. Similar for Λ^0 we have $\tau_{\Lambda^0} \approx 10^{-10}s$. What makes this happen? Strangeness? In 1953 Gell-Mann introduced the concept of ASSOCIATED PRODUCTION. K and Λ are strange particles with quantum number S (strangeness), they are produced in pairs with $S = \pm 1$ so no net strangeness is created (by strong interaction), those particles then go on to decay separately with $\Delta S = 1$ by the weak interaction. In the quark model we have the s-quark (strange quark) with $S = -1, Q = -\frac{1}{3}, B = +\frac{1}{3}$ and anti-s-quark has $S = +1, Q = +\frac{1}{3}, B = -\frac{1}{3}$. So S is arithmetically additive. All other quarks have $S = 0$, all leptons have no quarks hence no strangeness.

By convention

- K^0 has $S = +1$, is $d\bar{s}$, quark and anti-quark
- Λ^0 has $S = -1$, is uds , quark, quark, quark

Readily produce $K^0\Lambda^0$ pairs at accelerators, by $\pi^-p \rightarrow K^0\Lambda^0$, then $K^0 \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow p\pi^-$. This can be neatly represented by quark flow diagrams.

The s quark allows lots of “new” hadrons like Σ, Ξ, \dots . Strangeness is conserved in Strong&EM interaction but *not* in Weak.

Isospin

It has quantum number I , has been called *isotopic spin* and *isobaric spin*. It is similar to normal spin in that it has three components. Energy levels in mirror nuclei like ${}^7_3\text{Li}$, ${}^7_4\text{Be}$ are identical. If we look at processes π^+p & π^-n we find their cross-sections are identical. These are both things to do with Strong interaction and do not care about charge Q .

We know we can have proton&neutron in same energy state with parallel spins, but they are fermions and have to obey Fermi-Dirac distribution (and Pauli exclusion). So we assign new quantum number to differentiate proton&neutron so can exist in same energy state

$$\begin{aligned} I_3 &= +\frac{1}{2} \text{ for } p \\ I_3 &= -\frac{1}{2} \text{ for } n \end{aligned}$$

this gives us that $I_3 = +\frac{1}{2}$ for u quark and $I_3 = -\frac{1}{2}$ for d quark. I_3 is arithmetically additive. It is zero for all other quarks and obviously it is zero for leptons (not made of quarks). Overall ISOSPIN quantum number is I which is vectorially additive, like L, S, J . Ordinary spin angular momentum number of states in spin multiplet = $2S + 1$, so for isospin number of substates in a isospin multiplet = $2I + 1$. These are particles with same I but different I_3 projections. For Strong interaction all $2I + 1$ states are degenerate (ie same mass). Look at proton&neutron, with $I_3 = \pm\frac{1}{2}$, $I = \frac{1}{2}$. (Missing stuff?)

$Q = +\frac{2}{3}$	$u, I_3 = \frac{1}{2}$	$c, C = +1$	$t, T = +1$
$Q = -\frac{1}{3}$	$d, I_3 = -\frac{1}{2}$	$s, S = -1$	$b, \tilde{B} = -1$

Table 4: table of quarks and their properties.

We now have a redundancy in quantum number(Q, I), So we define $Q_q = \frac{B+S}{2} + I_3$, some people call $B + S$ hypercharge. All of these quantum numbers are arithmetically additive, so for a hadron we can write $Q_H = \frac{B+S}{2} + I_3$. This is called the Gell-Mann-Nishijima Relationship.

Note for future, extend the quark model from $uds \rightarrow udsct$. uct all have charge $+\frac{2}{3}$ and dst have charge $-\frac{1}{3}$.

SO we can extend expression for $Q_q = \frac{B+S+C+\tilde{B}+T}{2} + I_3$.

We have isospin triplet, for example the pion,

$$\pi^- (I_3 = -1), \pi^0 (I_3 = 0), \pi^+ (I_3 = 1)$$

all with $I = 1$, triplet as $2I + 1 = 3$.

Following strong interactions for the kaon.

$$\begin{aligned} \pi^+ n &\rightarrow K^0 \Sigma^+ \\ &00 \quad +1 - 1 \\ \pi^+ p &\rightarrow K^+ \Sigma^+ \\ &00 \quad +1 - 1 \\ \pi^- p &\rightarrow K^+ K^- n \\ &00 \quad +1 - 10 \end{aligned}$$

writing strangeness underneath. This tells us that K^+ has $S=+1$ made of $(u\bar{s})$ and that K^- has $S=-1$ made of $(\bar{u}s)$. This gives us a kaon triplet of K^-, K^0, K^+ , this tempts us to say they have $I = 1$, but for $K^+ Q = \frac{3}{2}$ which is wrong as we just worked out it has charge 1. But know that k-plus and k-minus have different $S(+1$ and $-1)$. cannot be part of same isospin multiplet. We get $K\text{-zero}(d\bar{s})$ and $K\text{-plus}(u\bar{s})$ with isospin $I=1/2$, Similarly we can get $K\text{-minus}(\bar{u}s)$ and $K\text{-bar-zero}(ds)$.

Isospin conservation

Form strong interaction and its charge independence we introduced I and I_3 and they are conserved. The EM interaction is not independent of charge which leads to I not being conserved, but the Gell-Mann-Nisijima relationship must still be true. Which leads to conservation of I_3 , as everything else in relationship is conserved.

In weak interaction S is not conserved, using GMN relationship we get that I_3 is not conserved.

Back to the quark model. We already know baryons have qqq (fermions) and Mesons $q\bar{q}$ (bosons). Which gives quarks have $1/2$ integral spin. Start by

	strong	EM	weak
I	yes	no	no
I_3	yes	yes	ni

Table 5: conservation of I and I_3 for each interaction.

Figure 16: We know a photon can split up into quark and anti-quark, as parity before is -1, it must be -1 after wards. This gives $p(q)=-p(\bar{q})$.

only consider lowest mass/energy combinations, we will only consider uds and not cbt as they have higher mass. Also only consider cases where there is no relative angular momentum between quarks, $L = 0$, $J = L + S = S$.

Baryons are made of qqq can have angular momentum. Two possible combinations two spins up one down \rightarrow spin=1/2 or spins all up \rightarrow spin=3/2. If we try all combinations of uds for a three quark thing(baryon) we get 10 possible combinations with $J=\text{spin}=1/2$ and ten with $J=\text{spin}=3/2$.

For fermions the total wavefunction must be anti-symmetric(Pauli).

$$\Psi \propto \psi_{space}\psi_{spin}\psi_{colour}$$

where ψ_{space} is symmetric for lowest energy state, ψ_{colour} must be anti-symmetric, like quarks in state together must have different colors. By deduction ψ_{spin} must be symmetric, otherwise Ψ can not be anti-symmetric. This means all like quarks in lowest energy combinations must have parallel (angular momentum) spins.

This means we cant have uuu , ddd or sss states for the $J=1/2$ state, these three combinations have parallel spin, which would give $J=3/2$.

For uud , dds , uus , uss , etc there can only be one possible arrangement they have two spin up one spin down.

For uds we can have spins with two different independent combinations. spins can either be up,up,down or up,down,up. These two states have $S=-1$, $I_3=0$, this implies on state with $I=0$ (this is Λ^0 particle) and the other $I=1$ (this is Σ^0). By changing an u or a d quark to a d or u quark we can generate the isospin partners. This works for the Σ but not for the Λ . Why? If we did change quarks for Λ we would end up having like quarks with same spin which is forbidden.

Now we turn to $J=3/2$, all ten possible combinations must have all spins parallel, No additional constraints, which allows for only one possible solution for each combination.

Parity It is an operator that reflects the position vector through origin. Particles have “intrinsic” parity, parity is multiplicative, it is conserved in strong, EM interactions but not in weak, parity of γ is -1.

In general for fermions we have $\text{parity}(\text{particle})=-\text{parity}(\text{antiparticle})$, by convention $\text{parity}(q)=+1$ and $\text{parity}(\bar{q})=-1$. Overall parity of the system is $P = p_1 \times p_2 \times p_3 \times \dots$

In lowest energy states($L=0$) we have $p(\text{baryons}, qqq) = 1^3 = +1$, $p(\text{antibaryons}, \bar{q}\bar{q}\bar{q}) = -1^3 = -1$ and $p(\text{mesons}, q\bar{q}) = +1(-1) = -1$.

This nice diagram predicted a new particle with $J=3/2$ and sss , $B = 1/3 + 1/3 + 1/3 = 1$ (its a baryon), $Q = -1/3 - 1/3 - 1/3 = -1$, $S = -1 - 1 - 1 = -3$ and its mass $M = 1676 MeV$ from the fact that every time you change a u or d to a s quark you add about $145 MeV$.

They could also predict its lifetime (of about $10^{-10}s$). There is now predicted particle with $S \leq -3$ it can decay via strong interaction (S conserved) $\Omega^- \rightarrow K^- \Xi^0$, but sum of mass ($494 + 1315 = 1809$) of decay products is bigger than its original mass. This tells us that a decay must involve a change in S, hence it must decay via weak interaction. In bubble chamber later (K- beam going into a hydrogen target) they found $K^- p \rightarrow \Omega^- K^+ K^0$, $\Delta S = 0$ so its a strong interaction process. The Ω^- decays into $\Xi^0 \pi^-$, with $|\Delta S| = 1$.

27.11.2006

Evidence for quarks

Explains all super multiplets, this is a bit dubious. It also explains cross sections. At high energies, we smash together $\sigma(\pi^+ p)$ or $\sigma(pp)$. If we count the probabilities of the interactions. As $\pi^+ + p$ tries to smash two quarks into three quarks and pp smashes three into three we would expect $\sigma(\pi^+ p) = \frac{2}{3} \sigma(pp)$, which is spot on.

Third evidence is scattering experiments. For example Rutherford who fired alpha particles into gold foil. Look at the angular distribution of scattered alphas. We can use similar principle to scatter probes of a target and look at angular distribution which will tell us something about structure of hadrons. We need resolving power of $\leq 10^{-18}m$, this gives a $\Delta p \approx 100 GeV$. As quarks interact via all interactions (weak, strong, EM). All scattering experiments show Hadrons have point-like scattering centers with fractional electric charge and account for 1/2 energy of hadron (rest is binding energy due to gluons).

ll this suggests that Quarks are real – this begs the questions: Do free quarks exist? In order to answer this we try to knock out a quark from a proton. In order to do this you need a high energy projectile, which will produce a jet of hadrons. Look for example at electron and positron annihilating to photon, then producing quark, anti quark pair. So far no one has ever found one, only always a jet of hadrons. This fits with our predictions that there are no free quarks.

For higher energy projectiles we can use cosmic rays. Search for McCusker as he is one person that claims to have seen this.

If we want to go to higher energy still, go to the Big Bang. If free quarks were produced back then the lightest one ($B=1/3$, $Q=2/3$, $-1/3$) would have nothing to decay to. In 1977 Fairbank did a Millikan oil drop kind of experiment with niobium balls. But still no one believes him.

Colour

Needed because we need a source of strong interaction (like electric charge for EM interaction). Furthermore we have violated Pauli principle many times already. Consider the Ω^- , it is made of sss with all spins aligned and $J=3/2$. Quarks are fermions so we need additional distinguishing quantum number. This will also explain why we don't see free quarks.

Need to ensure composite hadrons don't have this property. All quarks come in three "colour" varieties. All hadrons must be "white", "colorless" or "colour

singlet" states. Strong interaction is between colour charges. The Ω^- is hence made of $s_R s_G s_B$.

Importantly gluons also have colour, recall that γ do not have electric charge. Gluons are either $R\bar{B}$, $R\bar{G}$, $\bar{R}B$, $\bar{R}G$, $\bar{B}G$, $B\bar{G}$ and two linear combinations of $R\bar{R}$, $B\bar{B}$, $G\bar{G}$. If you want to know about these linear combinations then read Perkins, one of the recommended books.

Quarks in hadrons interact by transfer of gluons, which changes quark colors. Like charge colour is conserved at every vertex. This whole theory is called Quantum Chromodynamics.

Still not answered why there is no free quarks, answer is "quark confinement! Quarks can emit virtual gluons which have colour. Gluons have colour therefore they interact between themselves. This means the emitted gluon splits into two gluons, these recombine and then the gluon comes back to the quark. If we now introduce a "test quark" X. This quark sees "normal" (relatively weak) colour charge of Q.

Important thing to take away is force between quarks (attractive) INCREASES as separation INCREASES.

Quarks within hadrons appear "free" (close together, $\leq 10^{-15}$ m – relatively little force – asymptotic freedom. The fact that force increases as distance increases causes CONFINEMENT.

If we try to knock a quark out of say a meson, what we get is a quark and anti-quark moving apart from each other. Remember that we draw gluons as springs. So if we have enough momentum the "spring" will break. At the new, "open" ends of the springs (gluons) we will instantly have a new quark, anti-quark pair produced. This will happen again and again, until we used up all our energy, then we have a whole bunch of quark, anti quark pairs connected by gluons, our jet of hadrons.

Evidence for colour The fact that Ω^- exists, hence there must be a feature such as colour, this is cheating though. Particle decay rates, $\pi^0 \rightarrow 2\gamma$, the reason we need two photons is that we need to conserve momentum. Calculated QED decay rate is too slow! Experimental lifetime is less than expected by a factor of three. If we introduce colour somehow magically it works out. I'm not quite convinced.

4.12.2006

Ratio

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadron})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = \frac{\sigma_{had}}{\sigma_{\mu}}$$

the Feynman diagram for the top bit of the ratio is ee annihilation followed by two jets of hadrons. It has two vertices, A and B. So $\sigma_{had} \propto \text{coupling}_A \times \text{coupling}_B \propto Q_e^2 Q_q^2$, Q is charge of electron and quark.

For the denominator we have again diagram of annihilation but this time producing muons. Cross section is $\sigma_{\mu} \propto Q_e^2 \times Q_{\mu}^2$.

So we get a ratio of

$$R = \frac{Q_q^2}{Q_{\mu}^2}$$

the numerator must take account of all $q\bar{q}$ pairs kinematically allowed to be formed at given E_{cm} . For example at $E_{cm} = 2GeV$ we cant produce $c\bar{c}$ pairs

we have

$$R = \frac{(2/3)^2 + (-1/3)^2 + (-1/3)^2}{1}$$

for u,d,s quarks. This gives $R = \frac{2}{3}$, and we get $R = 2$ in experiments. If we do it at $E_{cm} = 11\text{GeV}$ we can produce bottom but not top. We get $R = \frac{11}{9}$ expected but experimentally it is $\frac{11}{3}$. The way to solve this is to introduce three colors. So we get $R = 3 \sum Q_i^2$, with $i=u,d,s,c,b,t$. If we plot R vs energy we see three jumps so far, each time you cross the threshold that allows you to produce a new quark. This method is also used to discover new quarks.

Where are we now? We have our three families of quarks and leptons. We have our force bosons, gluon(strong, range $\sim 1\text{E}-15\text{m}$, colour confinement), photon(EM, infinite range, no mass), W&Z(weak, range $\sim 1\text{E}-18\text{m}$).

A question that is remaining is how many more generations will there be? We use decay of Z^0 which can be produced in great numbers at LEP set to $E_{cm} = M_{Z^0}$. Smash e^+e^- into each other, this will produce a Z^0 . The Z^0 can decay to either quarks(hadron jets), lepton pairs(e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$) or neutrino pairs. First two are easy to detect, the last one is impossible to detect. Something called Lepton universality says that cross sections for each neutrino pair is the same.

No 4th neutrino type providing

- ν_4 would have mass $< \frac{M_{Z^0}}{2}$, this is not really a problem as we think that neutrinos have no mass anyway.
- ν_4 would have normal coupling Z^0 , ie it obeys lepton universality.

This all suggests there are only three neutrinos which implies there are no more leptons either, as they always come in pairs. From this we “deduce” by symmetry that there aren’t any more quarks either.

Hot Topics

Neutrino masses Initially thought to have zero mass. This is OK with Standard model. Until a few years ago everything was OK and no experiment ever showed that this idea was wrong. It has a few problems though.

- Solar neutrino problem(ν_e problem)
- Atmospheric neutrino problem(ν_μ problem). Cosmic ray protons interact when they hit the atmosphere. Produce under anderem Pions. These Pions are very short lived, decaying to $\nu_\mu\mu$. The μ is short lived to, decays to $e\nu_e\nu_\mu$. So we expect the ratio of $\frac{\nu_\mu}{\nu_e} \approx 2$. Though it was found to be 1.3

as this is a hot topic we dint have a good answer yet. Preferred solution to this is to give the neutrino mass and that all three types have different masses. Then we can have oscillations between flavors. This obviously violates conservation of lepton flavor. There is a good article in “Scientific American” about this.

11.12.2006

Higgs Boson Standard Model particles have zero mass. Higgs theory, says that particles acquire mass by their interaction with a field. Amount of mass depends on strength of interaction. All fields have associated with them an interaction boson. So the Higgs field should have one too, the Higgs Boson. These are all real and we should be able to detect them. Predict it will couple strongest to most massive particles. Mass not predicted exactly but expected to be $\leq 125\text{GeV}$. Expect dominant decay expected to be $H^0 \rightarrow b\bar{b}$. It is not yet found.

GUTs aims to unify all interactions. We know that Strong interaction gets weaker as energy increases & distances probed decrease. Electroweak gets stronger as energy increases & distances probed decrease. GUT unification predicts two new particles at 10^{15}GeV , the GUT unification energy. IT also predicts the decay of the proton with a lifetime of 10^{31} years.

Supersymmetry All current particles & interaction mediators are either fermions or bosons. For every 1/2 spin fermion there are integer spin partner.

For every integer boson we have an 1/2 spin partner.