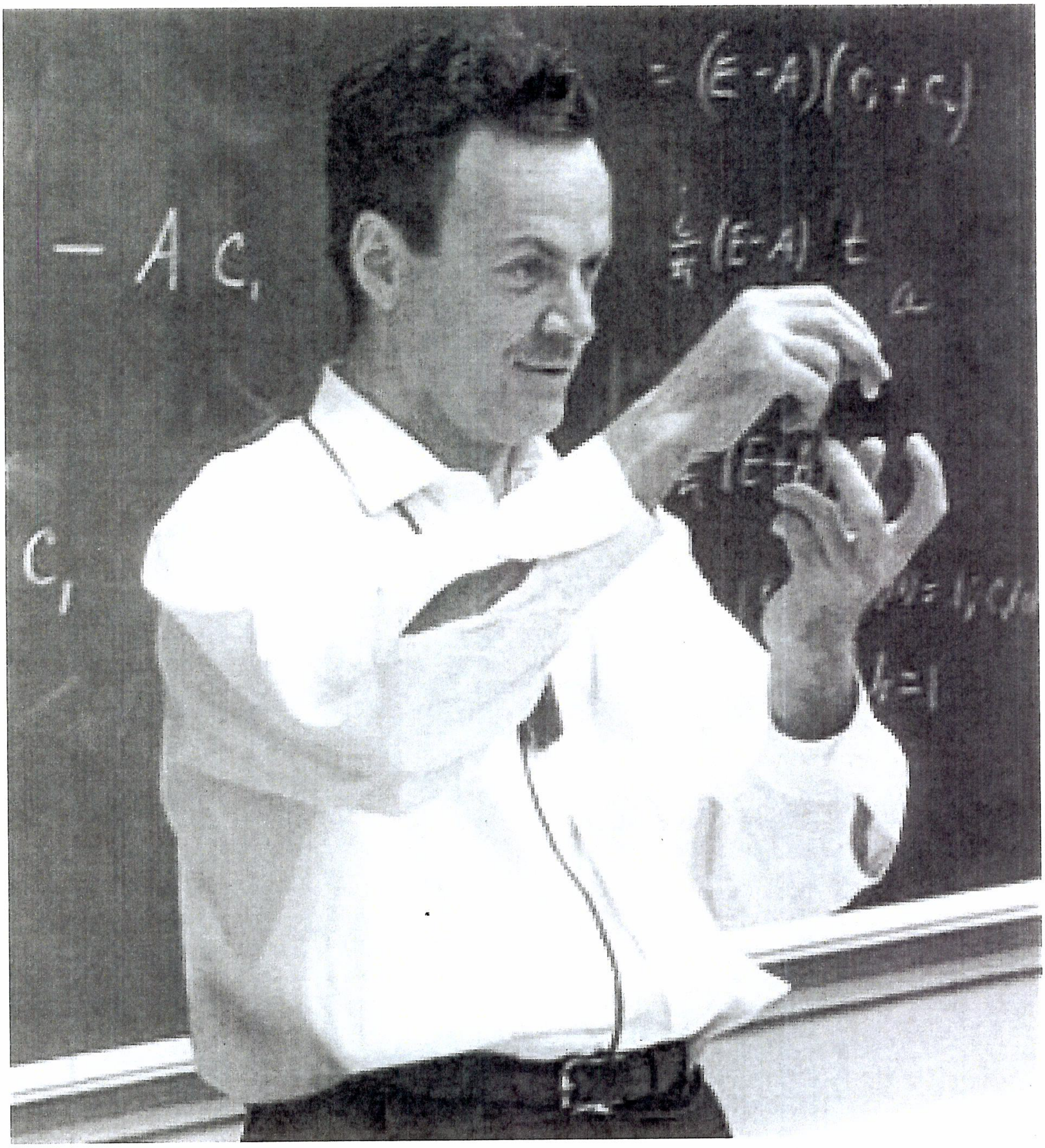


Particle Physics Pack

Particle Physics – the Basics!

Leptons

- Not made up of quarks
- Mostly 'light' particles (but not all)
- Do not 'feel' the strong interaction
- Have a lepton number, L = 1
- Antileptons have L = -1

Examples include:
Electron, e^-
Muon, μ^-
Tau, τ^-
Neutrinos (e, μ and τ type)
Positron, e^+ (antilepton)

Hadrons

- Made up of quarks
- Mostly 'heavy' particles (but not all)
- 'Feel' the strong interaction
- Of two types.......

Baryons

- Stupid name - not named after someone called Barry!
- Consist of 3 quarks
- Have a Baryon number, B = 1
- Antibaryons have B = -1
- Examples include:
  proton, neutron, Σ particles

Mesons

- Consist of quark – antiquark
- Have a Baryon number, B = 0 ....
  ....because they're not Baryons!
- Examples include:
  π particles (pions), K particles (kaons)

Quarks

- Only found in Hadrons
- Can't be separated
- Have charges of $+2/3e$ or $-1/3e$ (opposite for antiquarks)
- 6 of them in total
- We only meet particles with the first 3 ....

  up, down and strange (u, d, s)

Strange Particles

- Particles with strange quarks (or antiquarks)
- Fairly obvious, really!!!
- Have quantum number strangeness, S
- This can vary between -3 and + 3 depending on number of strange quarks
- Examples include:
  Σ particles, K particles

Gauge Bosons

- Involved in interactions
- Only exist for a very short time
- Different type for each interaction

Strong – Gluons
Electromagnetic – Photons
Weak – W^+, W^- and Z
Gravity - Gravitons

Let's draw Feynman diagrams!

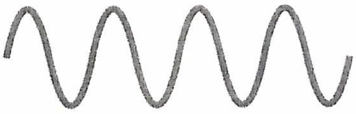
There are few things more iconic of particle physics than **Feynman diagrams**. These little figures of squiggly show up prominently on particle physicists' chalkboards alongside scribbled equations.

The simplicity of these diagrams has a certain aesthetic appeal, though as one might imagine there are many layers of meaning behind them. The good news is that's it's really easy to understand the first few layers and today you will learn how to draw your own Feynman diagrams and interpret their physical meaning.

You do not need to know any fancy-schmancy maths or physics to do this!

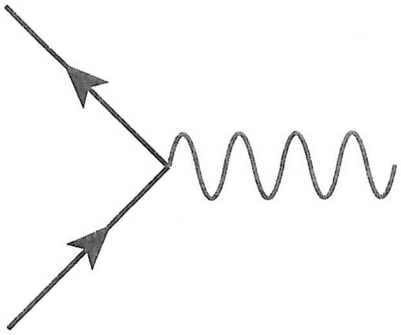
For now, think of this as a game. You'll need a piece of paper and a pen/pencil. The rules are as follows (read these carefully):

1. You can draw two kinds of lines, a straight line with an arrow or a wiggly line:



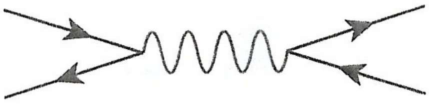
You can draw these pointing in any direction.

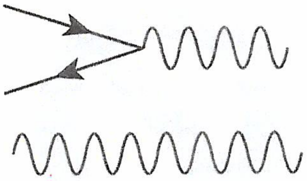
2. You may *only* connect these lines if you have two lines with arrows meeting a single wiggly line.



Note that the orientation of the arrows is important! You *must* have exactly one arrow going into the vertex and exactly one arrow coming out.

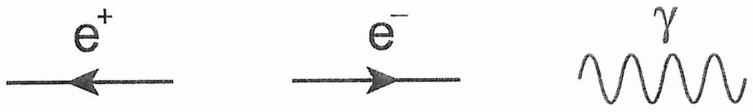
3. Your diagram should only contain connected pieces. That is every line must connect to at least one vertex. There shouldn't be any disconnected part of the diagram.





In the image above the diagram on the left is allowed while the one on the right is not since the top and bottom parts don't connect.

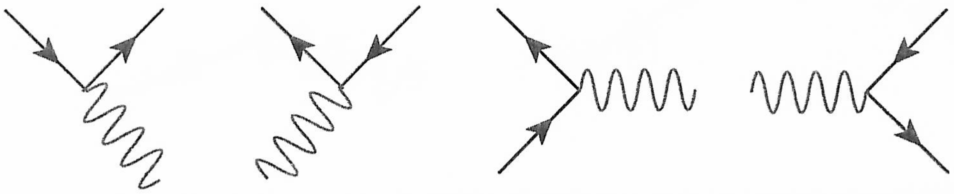
fact, you can think about the arrow as pointing in the direction of the flow of electric charge. As a summary, we our particle content is:



(e+ is a positron, e- is an electron, and the gamma is a photon… think of a gamma ray.)

From this we can make a few important remarks:

- The interaction with a photon shown above secretly includes information about the conservation of electric charge: for every arrow coming in, there must be an arrow coming out.
- But wait: we can also rotate the interaction so that it tells a different story. Here are a few examples of the different ways one can interpret the single interaction (reading from left to right):



These are to be interpreted as: (1) an electron emits a photon and keeps going, (2) a positron absorbs a photon and keeps going, (3) an electron and positron annihilate into a photon, (4) a photon spontaneously "pair produces" an electron and positron.

On the left side of a diagram we have "incoming particles," these are the particles that are about to crash into each other to do something interesting. For example, at the LHC these 'incoming particles' are the quarks and gluons that live inside the accelerated protons. On the right side of a diagram we have "outgoing particles," these are the things which are detected after an interesting interaction.

For the theory above, we can imagine an electron/positron collider like the the old LEP and SLACfacilities. In these experiments an electron and positron collide and the resulting outgoing particles are detected. In our simple QED theory, what kinds of "experimental signatures" (outgoing particle configurations) could they measure? (e.g. is it possible to have a signature of a single electron with two positrons? Are there constraints on how many photons come out?)

So we see that the external lines correspond to incoming or outgoing particles. What about the internal lines? These represent **virtual** particles that are never directly observed. They are created quantum mechanically and disappear quantum mechanically, serving only the purpose of allowing a given set of interactions to occur to allow the incoming particles to turn into the outgoing particles. We'll have a lot to say about these guys in future posts. Here's an example where we have a virtual photon mediating the interaction between an electron and a positron.

1. **What is the significance of the *x* and *y* axes?**

   These are really spacetime diagrams that outline the "trajectory" of particles. By reading these diagrams from left to right, we interpret the *x* axis as time. You can think of each vertical slice as a moment in time. The *y* axis is roughly the space direction.

2. **So are you telling me that the particles travel in straight lines?**

   No, but it's easy to mistakenly believe this if you take the diagrams too seriously. The *path* that particles take through actual space is determined not only by the interactions (which are captured by Feynman diagrams), but the kinematics (which is not). For example, one would still have to impose things like momentum and energy conservation. The point of the Feynman diagram is to understand the interactions along a particle's path, not the actual trajectory of the particle in space.

3. **Does this mean that positrons are just electrons moving backwards in time?**

   In the early days of quantum electrodynamics this seemed to be an idea that people liked to say once in a while because it sounds neat. Diagrammatically (and in some sense mathematically) one can take this interpretation, but it doesn't really buy you anything. Among other more technical reasons, this viewpoint is rather counterproductive because the mathematical framework of quantum field theory is built upon the idea of causality.

4. **What does it mean that a set of incoming particles and outgoing particles can have multiple diagrams?**

   In the examples above of two-to-two scattering I showed two different diagrams that take the in-state and produce the required out-state. In fact, there are an infinite set of such diagrams. (Can you draw a few more?) Quantum mechanically, one has to sum over all the different ways to get from the in state to the out state. This should sound familiar: it's just the usual sum over paths in the double slit experiment that we discussed before. We'll have plenty more to say about this, but the idea is that one has to add the mathematical expressions associated with each diagram just like we had to sum numbers associated with each path in the double slit experiment.

5. **What is the significance of rules 3 and 4?**

   Rule 3 says that we're only going to care about one particular chain of interactions. We don't care about additional particles which don't interact or additional independent chains of interactions. Rule 4 just makes the diagrams easier to read. Occasionally we'll have to draw curvy lines or even lines that "slide under" other lines.

6. **Where do the rules come from?**

   The rules that we gave above (called **Feynman rules**) are essentially the definition of a theory of particle physics. More completely, the rules should also include a few numbers associated with the parameters of the theory (e.g. the masses of the particles, how strongly they couple), but we won't worry about these

Table 1 Four Fundamental Interactions

Interaction	Relative Strength	Range	Mediating Particle Name	Mass	Charge	Spin
Strong	1	Short ($\sim$1 fm)	Gluon	0	0	1
Electromagnetic	$\frac{1}{137}$	Long ($1/r^2$)	Photon	0	0	1
Weak	10^{-9}	Short ($\sim$0.001 fm)	$W^{\pm}$, Z^0	80.4, 91.2 GeV/c^2	$\pm e$, 0	1
Gravitational	10^{-38}	Long ($1/r^2$)	Graviton	0	0	2

Table 2 The Six Leptons

Particle Name	Symbol	Anti-particle	Mass (MeV/c^2)	L_e	L_μ	L_τ	Lifetime (s)	Principal Decay Modes
Electron	e^-	e^+	0.511	+1	0	0	Stable	
Electron neutrino	ν_e	$\bar{\nu}_e$	$<3 \times 10^{-6}$	+1	0	0	Stable	
Muon	μ^-	μ^+	105.7	0	+1	0	2.20×10^{-6}	$e^- \bar{\nu}_e \nu_\mu$
Muon neutrino	ν_μ	$\bar{\nu}_\mu$	<0.19	0	+1	0	Stable	
Tau	τ^-	τ^+	1777	0	0	+1	2.9×10^{-13}	$\mu^- \bar{\nu}_\mu \nu_\tau$ or $e^- \bar{\nu}_e \nu_\tau$
Tau neutrino	ν_τ	$\bar{\nu}_\tau$	<18.2	0	0	+1	Stable	

Table 3 Some Hadrons and Their Properties

Particle	Mass (MeV/c^2)	Charge Ratio, Q/e	Spin	Baryon Number, B	Strangeness, S	Mean Lifetime (s)	Typical Decay Modes	Quark Content
Mesons								
π^0	135.0	0	0	0	0	8.4×10^{-17}	$\gamma\gamma$	$u\bar{u}$, $d\bar{d}$
π^+	139.6	+1	0	0	0	2.60×10^{-8}	$\mu^+\nu_\mu$	$u\bar{d}$
π^-	139.6	−1	0	0	0	2.60×10^{-8}	$\mu^-\bar{\nu}_\mu$	$\bar{u}d$
K^+	493.7	+1	0	0	+1	1.24×10^{-8}	$\mu^+\nu_\mu$	$u\bar{s}$
K^-	493.7	−1	0	0	−1	1.24×10^{-8}	$\mu^-\bar{\nu}_\mu$	$\bar{u}s$
η^0	547.3	0	0	0	0	$\approx 10^{-18}$	$\gamma\gamma$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$
Baryons								
p	938.3	+1	$\frac{1}{2}$	1	0	Stable	—	*uud*
n	939.6	0	$\frac{1}{2}$	1	0	886	$pe^-\bar{\nu}_e$	*udd*
Λ^0	1116	0	$\frac{1}{2}$	1	−1	2.63×10^{-10}	$p\pi^-$ or $n\pi^0$	*uds*
Σ^+	1189	+1	$\frac{1}{2}$	1	−1	8.02×10^{-11}	$p\pi^0$ or $n\pi^+$	*uus*
Σ^0	1193	0	$\frac{1}{2}$	1	−1	7.4×10^{-20}	$\Lambda^0\gamma$	*uds*
Σ^-	1197	−1	$\frac{1}{2}$	1	−1	1.48×10^{-10}	$n\pi^-$	*dds*
Ξ^0	1315	0	$\frac{1}{2}$	1	−2	2.90×10^{-10}	$\Lambda^0\pi^0$	*uss*
Ξ^-	1321	−1	$\frac{1}{2}$	1	−2	1.64×10^{-10}	$\Lambda^0\pi^-$	*dss*
Δ^{++}	1232	+2	$\frac{3}{2}$	1	0	$\approx 10^{-23}$	$p\pi^+$	*uuu*
Ω^-	1672	−1	$\frac{3}{2}$	1	−3	8.2×10^{-11}	Λ^0K^-	*sss*
Λ_c^+	2285	+1	$\frac{1}{2}$	1	0	2.0×10^{-13}	$pK^-\pi^+$	*udc*

Conservation. (Will this happen?)

	K^+	$\rightarrow$	μ^+	$+\ \nu_\mu$	**Conserved?**	**Happens?**
Q(charge)						
B(Baryon Number)						
L(Lepton Number)						
S(Strangeness)						

	Λ	$\rightarrow$	p	$+\ \pi^-$	**Conserved?**	**Happens?**
Q						
B						
L						
S						

	Ξ^0	$\rightarrow$	p	$+\ \pi^0$	**Conserved?**	**Happens?**
Q						
B						
L						
S						

	μ^-	$\rightarrow$	e^-	$+\ \overline{\nu_e}$	$+\ \nu_\mu$	**Conserved?**	**Happens?**
Q							
B							
L							
S							

	Ω^-	$\rightarrow$	Ξ^0	$+\ \pi^-$	**Conserved?**	**Happens?**
Q						
B						
L						
S						

	Σ^0	$\rightarrow$	Λ	$+\ \gamma$	**Conserved?**	**Happens?**
Q						
B						
L						
S						

	Σ^+	$\rightarrow$	p	$+\ K^0$	**Conserved?**	**Happens?**
Q						
B						
L						
S						

	n	$\rightarrow$	p	$+\ e^-$	$+\ \nu_e$	**Conserved?**	**Happens?**
Q							
B							
L							
S							

	Δ^+	$\rightarrow$	π^+	$+\ \pi^0$	**Conserved?**	**Happens?**
Q						
B						
L						
S						

Meson	Symbol
Pion+	π^+
Pion-	π^-
Pion-0	π^0
Kaon+	K^+
Kaon-	K^-
Eta-0	η^0

Baryon	Symbol	Makeup
proton	p	uud
neutron	n	ddu
Lambda	Λ^0	uds
Sigma	Σ^+	uus
Sigma	Σ^0	uds
Sigma	Σ^-	dds
Xi	Ξ^0	uss
Xi	Ξ^-	dss
Delta	Δ++	uuu
Delta	Δ+	uud
Delta	Δ0	udd
Delta	Δ–	ddd
Omega	Ω–	sss

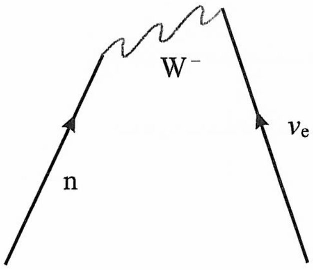
1. (a) A neutrino may interact with a neutron in the following way

$$\nu_e + n \Rightarrow p + e^-.$$

(i) Name the fundamental force responsible for this interaction.

....

(ii) Complete the Feynman diagram for this interaction and label all the particles involved.



(3)

(b) The neutral kaon, which is a meson of strangeness +1, may decay in the following way

$$K^\circ \Rightarrow \pi^+ + \pi^-.$$

(i) Apart from conservation of energy and momentum, state **two** other conservation laws obeyed by this decay and **one** conservation law which is **not** obeyed.

.... conservation law is obeyed

.... conservation law is obeyed

.... conservation law is not obeyed

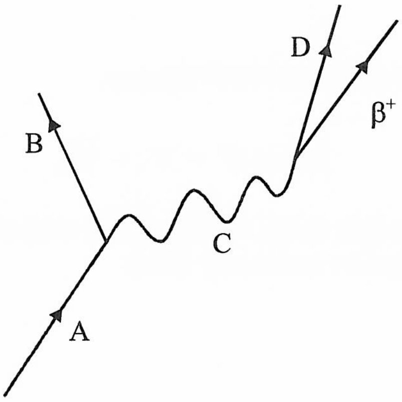
(ii) In the decay shown above, charge is conserved. Give another quantity that is conserved and a quantity that is not conserved in the decay of K^-.

quantity conserved ....

quantity not conserved ....

(6)

(c) The Feynman diagram below represents the β^+ decay process.



(i) What quantity changes continuously in moving from the bottom to the top of the diagram?

....

(ii) Name the particles represented by the letters A to D.

A ....

B ....

C ....

D ....

(iii) What type of interaction is responsible for β^+ decay?

....

(6)
(Total 14 marks)