HH0142 What Are the Building Blocks of Our Universe?

From the perspective of reductionism ...

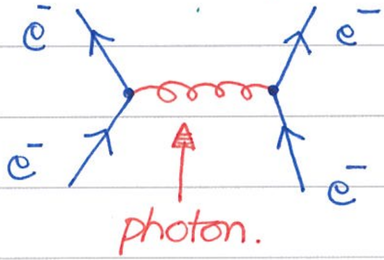
Biology → complicated interactions of chemical compounds 

Chemistry → complicated interactions of different atoms (elements) 

Physics → complicated interactions of e^-, p^+, n^0. Is this a complete understanding? From β decay, we know one more particle ν (neutrino).

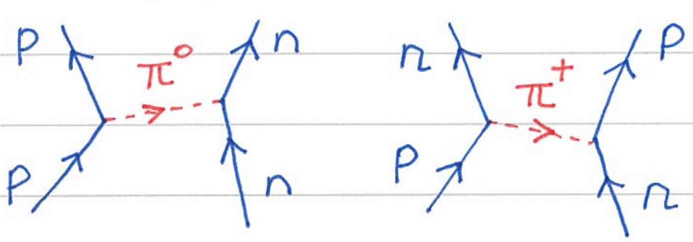
From Dirac's equation (quantum mechanics + special relativity) → e^-, p^+, n^0, ν all have antiparticles $e^+, \bar{p}, \bar{n}, \bar{\nu}$. The Q is ... Are these particles all we need to explain all matters in our universe?

⊘ Modern view of interaction. In modern physics, interactions between two particles are mediated by another particle. For instance, EM interactions are mediated by photons. The graph



is called Feynman diagram – a convenient theoretical tool but should not be confused as the true trajectories ☺

Yukawa earned his 1949 Nobel Prize for cooking up the 1st theory of nuclear force. He postulated that the interactions



between two nucleons can be described by exchange of mesons π^0, π^+, π^-.

meson = "middle" + on because $m_\pi c^2 \approx 140$ MeV

To estimate the mass of pions, one can make use of the uncertainty principle,

$$\Delta E \, \Delta t \approx \hbar$$

← $\Delta E > m_\pi c^2$ in the presence of virtual pion.

The existence of the pion would violate the energy conservation law if the particle existed for a time interval longer than $\Delta t \approx \hbar/\Delta E \approx \hbar/m_\pi c^2$. Because the pion cannot travel faster than the speed of light, the maximum distance it can travel is $\xi = c\Delta t$. The relation between $m_\pi c^2$ & ξ is

$$m_\pi c^2 \approx \frac{\hbar}{\Delta t} = \frac{\hbar c}{\xi} = \frac{(1.055\times10^{-34}\,J\cdot s)(3\times10^{8}\,m/s)}{10^{-15}\,m}$$

$$\rightarrow \quad m_\pi c^2 \approx 3.2\times10^{-11}\,J \approx 200\,MeV$$

estimate $m_\pi c^2$ by the interaction range ξ.

The estimate from the uncertainty principle is quite close to the measured value ☺

⊘ Classification of particles. Sorting the particles by their masses into three categories: Baryons, Mesons, Leptons.

Baryons:	p	938.3 MeV
	n	939.6 MeV
Mesons:	$\pi^\pm$	139.6 MeV
	π^0	135.0 MeV
Leptons:	e^-	0.511 MeV
	ν	< several eV

Ok, so life seems a bit more complicated now. But, the nightmare begins ... We start to find more baryons, $\Lambda^0, \Sigma^\pm, \Sigma^0, \Delta^{++}, \Delta^+, \Delta^0, \Delta^-, \Xi^0, \Xi^\pm, \Omega^\pm$ and so on ☹

And the story goes on and on. More mesons as well, $K^\pm, K^0, \eta, \bar{\eta}$ and so on. Not surprisingly, we also find more leptons, $\mu^-, \nu_\mu, \tau^-, \nu_\tau$. Basically, we have a zoo of fundamental particles. We should not expect them to be fundamental.

Let us introduce Baryon number (B) and Lepton number (L) to help us classifying the zoo.

	B	L
$p, n, \cdots$	1	0
$\pi^{\pm}, \pi^{0}, \cdots$	0	0
$e^{-}, \nu, \cdots$	0	1

Antiparticles have opposite B and L

It is quite interesting that both B and L are conserved in all physical processes! Here is the simple demo:

$n \rightarrow p + e^{-} + \bar{\nu}$

Baryon # $1 = 1 + 0 + 0$ ✓

Lepton # $0 = 0 + 1 + (-1)$ ✓

(1) Strange particles. But the conservation laws of B and L do not seem to explain all processes. For example, kaons (K mesons) are similar to pions in many aspects. Because there is no conservation law of mesons, one may expect that any # of kaons can be produced → this turns out to be WRONG.

$p + p \longrightarrow p + p + K^{+} + K^{-}$

$p + p \longrightarrow p + n + K^{+} + \bar{K}^{0}$

$p + p \longrightarrow p + \Lambda^{0} + K^{+}$

A new quantum # is in order

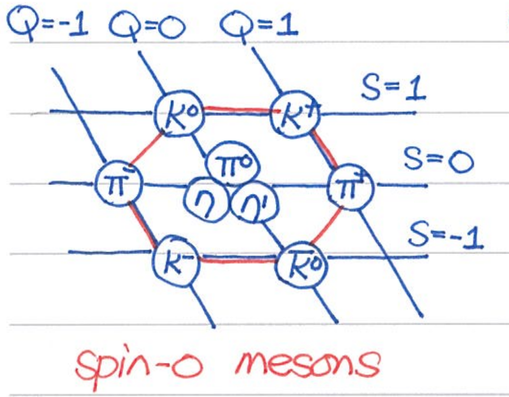
K^{+}, K^{0} $(S=1)$ baryon Λ^{0} $(S=-1)$

$K^{-}, \bar{K}^{0}$ $(S=-1)$ ← strangeness S

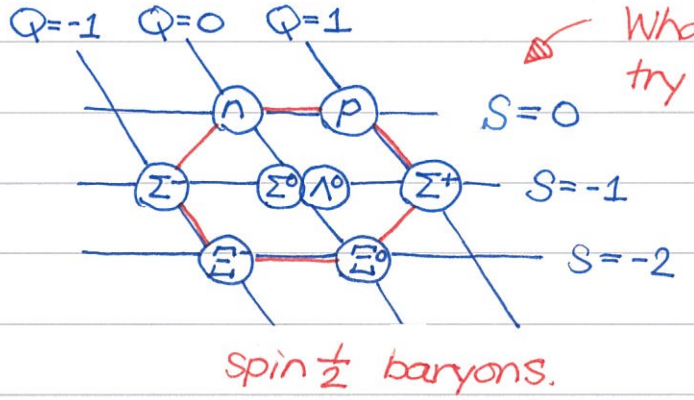
The strangeness for $p, n, \pi^{\pm}, \pi^{0}$ are all zero. It turns out that strangeness S is conserved except in weak interaction.

One can arrange the mesons and the baryons into the charts,

What does it try to tell us?



spin-0 mesons



spin $\frac{1}{2}$ baryons.

In 1964, it was suggested independently by Gellmann and Zweig that the charts can be explained by three quarks called up (u), down (d) and strange (s).

	Q	B	S
u	+2/3	1/3	0
d	−1/3	1/3	0
s	−1/3	1/3	−1

antiquarks $\bar{u}, \bar{d}, \bar{s}$ have opposite Q, B, S

Because $B=\frac{1}{3}$ for a quark, baryons consist of 3 quarks.

uud $\quad Q=\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$, $B=1$, $S=0 \rightarrow p$ (proton)

udd $\quad Q=\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$, $B=1$, $S=0 \rightarrow n$ (neutron)

uds $\quad Q=\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$, $B=1$, $S=-1 \rightarrow \Lambda^0$ strange particle.

You can basically work out the baryon chart this way. To avoid complications, I intentionally skip the composition rule of spins because they are quantum vectors.

What about mesons? A quark and antiquark will do the job. The pions in Yukawa's theory are not fundamental.

$u\bar{d} \quad Q=\frac{2}{3}+\frac{1}{3}=1 \quad S=0 \rightarrow \pi^+$

$d\bar{u} \quad Q=-\frac{1}{3}-\frac{2}{3}=-1 \quad S=0 \rightarrow \pi^-$

(π^+, π^-: antiparticles)

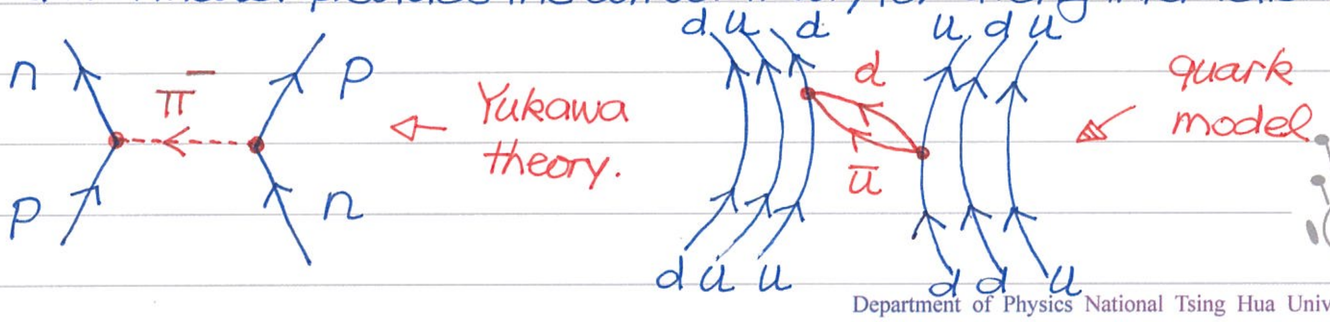
$d\bar{s} \quad Q=-\frac{1}{3}+\frac{1}{3}=0 \quad S=1 \rightarrow K^0$

$s\bar{d} \quad Q=-\frac{1}{3}+\frac{1}{3}=0 \quad S=-1 \rightarrow \bar{K}^0$

(K^0, $\bar{K}^0$: antiparticles.)

The neutral pion $\pi^0=\frac{1}{\sqrt{2}}u\bar{u}-\frac{1}{\sqrt{2}}d\bar{d}$ and η, η' are mixed $u\bar{u}, d\bar{d}, s\bar{s}$. All other mesons can be worked out in similar way.

Quark model provides the correct theory for strong interaction.



⑪ Standard model So, it seems that we finally find the building blocks of our universe: u, d, s quarks. Hum… not quite. The zoo of particles can be described by the so-called "Standard Model" with 3 generations of quarks and the corresponding leptons. The interactions are mediated by some gauge bosons:

1^{st} generation	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$
2^{nd} generation	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$
3^{rd} generation	$\begin{pmatrix} t \\ b \end{pmatrix}$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$

- g (gluon) — Strong
- γ (photon) — EM
- Z, $W^{\pm}$ } Weak

and the recently found H – Higgs boson, accounting the origin of the masses for the particles ☺

Although the Standard Model is quite successful in explaining many experimental data. It does not explain gravity. In addition, it does not explain the masses of neutrinos. At this point, we are not completely clear about how to describe all fundamental interactions in a coherent way.

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