Radiation Detector 2018/19 (SPA6309)

Nuclear and Particle Physics

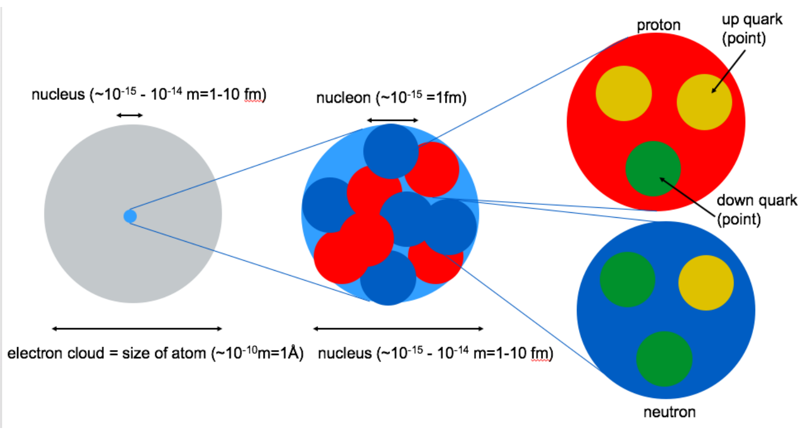
Nuclear physics

A **Nucleus** is the core of an atom. The plural is **nuclei**. And a nucleus is made up by **nucleons** which include **protons (+1 electric charge)** and **neutrons (0 electric charge)**. Protons and neutrons are attracted each other by **strong nuclear force**. The same force put together **quarks** to make nucleons, however, this force acts inside and outside of nucleons in a different way. As we see in tutorial 3, **mesons**, especially **pions (pi mesons)** mediate strong force and bind protons and neutrons.

An arbitrary nucleus is specified by 3 numbers, ${}^{A}_{Z}X^{N}$

- **Z (atomic number)**, the total number of protons.
- **A (mass number)**, the total number of nucleons.
- **N (neutron number)**, the total number of neutrons.

And $A = Z + N$, so you don't need to specify 3, but 2 is fine, let's say we specify Z and A. Moreover, if you specify the element X, say it's "carbon", then you are already saying there are 6 protons, so you don't need to say Z, either. So if you specify the element name and mass number, like ${}^{12}C$, there is no ambiguity which nucleus you are talking about. But just saying "carbon" is not enough. Because carbon has 6 protons, but the number of neutrons can be 6 or others. For example, 1% of carbon has 7 neutrons, namely ${}^{13}C$. These nuclei, same atomic number but different neutron number, are called **isotope.**



Radioactive decay

Radioactive materials emit **radiations** by **radioactive decay**. There are 3 main processes.

- **Alpha decay**, ${}^{A}_{Z}X_N \rightarrow {}^{A-4}_{Z-2}Y_{N-2} + \alpha$
- **Beta decay**, ${}^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}Y_{N-1} + e + \bar{\nu}_e$
- **Gamma decay**, ${}^{A}_{Z}X^*_N \rightarrow {}^{A}_{Z}X_N + \gamma$

Radioactive decay law

The **activity** (the rate of radioactive decay) goes down with exponential function. In other words, the amount of radioactive material decrease exponentially.

$$N(t) = N_0 exp(-\lambda t)$$

N_0 is the initial amount of a radioactive material, and $N_(t)$ describe the amount of it after time t. The amount decreases exponentially, with a function of **decay constant** λ. In particular,

$$t_{1/2} = \frac{ln(2)}{\lambda}$$

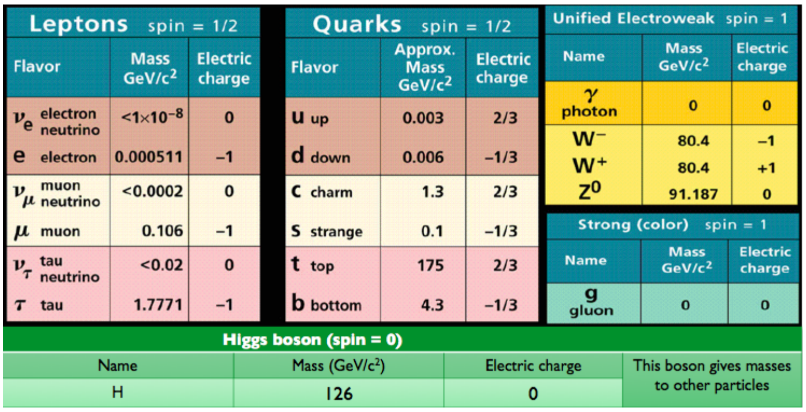
is called **half-life** where an amount of the initial radioactive material goes half. So after time $t_{1/2}$, it goes to half, then after another time $t_{1/2}$, it goes to a quarter of the initial amount, etc... it goes less and less quickly. If you use a logarithmic for the y-axis, you will see a straight line for the activity (or amount of the radioactive material) with a function of time.

Radiation detector, what is "visible" particles?

There are very limited number of "visible" particles.

1. long lived charged particles
2. photons

So the naive list of "visible" particles are γ, p, e, μ, $\pi^{\pm}$ (but not π°), $K^{\pm}$..., that's it!



Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Higgs boson (spin = 0)

Name	Mass (GeV/c²)	Electric charge	This boson gives masses to other particles
H	126	0	

Quarks

6 quarks can be classified to 3 **generations.** Baryon number, lepton number, and electric charge are all conserved. **Anti-particles** have opposite signs of them. All particles in the real world must have integer baron number and electric charge, this means you cannot take out single quark to the outside of nucleons.

symbol	*name*	*baryon number*	*lepton number*	*electric charge*	*mass*(MeV/c^2)
u	*up*	$\frac{1}{3}$	0	$+\frac{2}{3}$	~ 2
d	*down*	$\frac{1}{3}$	0	$-\frac{1}{3}$	~ 5
c	*charm*	$\frac{1}{3}$	0	$+\frac{2}{3}$	1275
s	*strange*	$\frac{1}{3}$	0	$-\frac{1}{3}$	95
t	*top*	$\frac{1}{3}$	0	$+\frac{2}{3}$	173×10^3
b	*bottom*	$\frac{1}{3}$	0	$-\frac{1}{3}$	4180

Leptons

6 leptons are also classified to 3 **generations.** Upper leptons are called **neutrinos**, and they have 0 electric charges. Lower leptons are called **charged lepton.** Neutrinos have tiny masses only measurable through **neutrino oscillations**, however, there is no problem to approximate their masses are 0 in any situations of particle interactions.

symbol	*name*	*baryon number*	*lepton number*	*electric charge*	*mass*(MeV/c^2)
ν_e	*electronneutrino*	0	1	0	~ 0
e^-	*electron*	0	1	-1	0.511
ν_μ	*muonneutrino*	0	1	0	~ 0
μ^-	*muon*	0	1	-1	106.6
ν_τ	*tauneutrino*	0	1	0	~ 0
τ^-	*tau*	0	1	-1	1777

Gauge bosons and Higgs boson

In the SM, particle interactions are described by exchanges of gauge bosons. **Photons** mediate the **electromagnetic** force, and **W and Z bosons (weak bosons)** mediate the **weak** force, and **gluons** mediate the **strong** force. Only quarks exchange gluons, and only particles with electric charges exchange photons, and all of them exchange weak bosons. Notice weak bosons are very heavy. Unless beam energy is higher than their masses, weak bosons are always **virtual** particles and don't propagate in the real space. For exmaple, β-decay is caused by a weak force, but weak boson is a virtual particle and it is a point in a neutron.

In 2012, two experiments at the Large Hadron Collider (LHC) announced the discovery of the **Higgs boson.** By this, all predicted particles within the SM were discovered. Higgs boson is responsible to give masses to all particles in the Standard Model. Higgs boson is also the first elementary particle boson with spin=0.

$Interactions$	$coupling$	$range$	$lifetime(s)$	$cross-section(cm^2)$
$strong$	1	$\sim 1fm \sim \frac{1}{m_\pi}$	$\sim 10^{-24}$	$\sim 10^{-26}$
			$(\Delta^{++} \to p\pi^+)$	$(\pi^+ + p \to \pi^+ + p)$
$electromagnetic$	$\sim 10^{-2}$	$\sim \infty$	$\sim 10^{-16}$	$\sim 10^{-30}$
			$(\pi^\circ \to \gamma\gamma)$	$(\gamma + p \to \pi^\circ + p)$
$weak$	$\sim 10^{-6}$	$\sim \frac{1}{m_W}$	$\sim 10^{-8}$	$\sim 10^{-38}$
			$(\pi^+ \to \mu^+\nu_\mu)$	$(\nu_\mu + n \to \mu^- + p)$
$gravity$	$\sim 10^{-38}$	$\sim \infty$	$\infty?$	$\sim 0?$

Interactions

Strength of each interaction is characterized by the **coupling**, how strongly each gauge boson couple to particles. For example, strong interaction couples strongly, which means strong force is very effective. If a particle can decay by the strong force, its lifetime is very short because it acts effectively and quick. If particles can interact with the strong force, its interaction cross-section is very large. There are 2 types of weak interactions, **charged current (CC)** interaction exchanges W boson, and **neutral current (NC)** interaction exchanges Z boson.

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Hadrons, baryons, and mesons

There are 2 types of **hadrons**. **Baryons** are made up with 3 quarks and baryon number is 1. **Mesons** are made up with 1 quark and 1 anti-quark, so the baryon number is 0.

Anti-particles have opposite baryon number and electric charge, but same mass. Notice neutral pion π° has no anti-particle, but neutral kaon K has anti-particle $\bar{K}$. These are clear once we see the quark combinations. π° is a super position of $u\bar{u}$ and $d\bar{d}$ wave functions. Lifetimes are very different depending on which force causes the decay. As we discussed above, strong force is very effective, this means any time when strong force is applicable, particles decay by the strong force and their lifetimes are very short. If the strong force is not available (for example decays of π° which cannot decay to any lighter hadrons), then particles choose electromagnetic force to decay. If electromagnetic force is not available (for example decays of muons), particles decay with weak force, and in this case lifetimes of particles can be much longer.

$symbol$	$combination$	$name$	$b\ number$	$e\ charge$	$mass(MeV/c^2)$	$lifetime(s)$
p	uud	$proton$	1	+1	938	$\infty?$
$\bar{p}$	$\bar{u}\bar{d}\bar{d}$	$anti-proton$	-1	-1	938	$\infty?$
n	udd	$neutron$	1	0	939	$15min$
Δ^{++}	uuu	$delta++$	1	+2	1232	10^{-24}
Λ^0	uds	$lambda$	1	0	1116	10^{-10}
π^+	$u\bar{d}$	$pion+$	0	+1	139.6	10^{-8}
π°	$1/\sqrt{2}(u\bar{u}+d\bar{d})$	$pion0$	0	0	135.0	10^{-16}
π^-	$d\bar{u}$	$pion-$	0	-1	139.6	10^{-10}
K^+	$u\bar{s}$	$kaon+$	0	+1	493.7	10^{-8}
K^0	$d\bar{s}$	$kaon0$	0	0	497.6	$10^{-11}-10^{-8}$
$\bar{K}^0$	$s\bar{d}$	$kaon0bar$	0	0	497.6	$10^{-11}-10^{-8}$
K^-	$s\bar{u}$	$kaon+$	0	-1	493.7	10^{-8}