PHYS3051 Content Notes

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1 Week 1

1.2 – The Photon (1900 - 1924)

Electromagnetic radiation is ***quantized***, coming in little packages of energy

$$E = h\nu \tag{1.1}$$

where ν is the frequency of the radiation and $h = 6.626 \times 10^{-27}$ erg.s is Planck's constant.

Photoelectric effect: when an incoming photon hits an electron in metal, giving up its energy of $h\nu$, an excited electron breaks through the metal surface, losing in the process an energy w (the so called *work function* of the material). The electron emerges (free) with an energy of

$$E \leq h\nu - w \tag{1.3}$$

1.4 – Antiparticles (1930 - 1956)

For every kind of particle there must exist a corresponding ***antiparticle***, with the same mass but opposite electric charge. The standard notation for antiparticles is an overbar. For example, p denotes a proton and $\overline{p}$ an antiproton. In some cases, it is customary simply to specify the charge. Most people write e^+ for the positron (not $\overline{e}$) and μ^+ for the antimuon. Some neutral particles are their *own* antiparticles. For example, the photon: $\overline{\gamma} \equiv \gamma$.

The antineutron differs from a neutron only in quantum number. Although the net charge of a neutron is zero, the neutron *does* have a charge structure (positive at the center and near the surface, and negative in between) and a magnetic dipole moment. These have opposite signs for $\overline{n}$.

There is a general principle in particle physics that goes under the name of ***crossing symmetry.*** Suppose that a reaction of the form

$$A + B \to C + D$$

is known to occur. Any of these particles can be 'crossed' over to the other side of the equation, provided it is turned into its antiparticle, and the resulting interaction will also be allowed. For example,

$$A \to \overline{B} + C + D$$
$$A + \overline{C} \to \overline{B} + D$$

In addition, the *reverse* reaction occurs: $C+D \to A+B$, but technically this derives from the principle of *detailed balance* rather than from crossing symmetry. However, there is one important caveat in all this: conservation of energy may veto a reaction that is otherwise permissible. e.g. a minimum kinetic energy may need to occur to make up for some mass difference in the reaction.

2 Week 2

1.6 – Strange Particles (1947-1960)

A new particle, with at least twice the mass of the pion was discovered, called the kaon, K^0. This decays via

$$K^0 \to \pi^+ + \pi^- \tag{1.22}$$

A positively charged kaon was also discovered, with

$$K^+ \to \pi^+ + \pi^+ + \pi^- \tag{1.23}$$

Soon after, the lambda, Λ, was discovered, which decays via

$$\Lambda \to p^+ + \pi^- \tag{1.24}$$

which means that the lambda is substantially heavier than the kaon. The lambda belongs with the proton and neutron in the baryon family.

What stops the proton from spontaneously decaying? A law of *conservation of baryon number* was proposed: assign to all baryons a 'baryon' number $A = +1$, and to the antibaryons $A = -1$ – the total baryon number is conserved in any physical process. Since the proton is the lightest baryon, it has nothing to decay down to (while still maintaining baryon number), and so it remains stable.

Unlike leptons and baryons, there is *no* conservation of mesons. In pion decay ($\pi^- \to \mu^- + \overline{\nu}_\mu$) a meson disappears, and in lambda decay a meson is created.

Strange particles are produced by the strong force (the same that holds atomic nuclei together), but they decay by the weak force (the one that accounts for beta decay and all other neutrino processes). Strange particles are also produced in pairs (so called ***associated production***). Each particle was assigned a new property called *strangeness* that (like charge, lepton number, and baryon number) is conserved in any strong interaction. But, unlike those others, is *not* conserved in a weak interaction. Leptons and photons don't experience strong forces at all, so strangeness does not apply to them.

1.8 – The Quark Model (1964)

The quarks come in three types (or 'flavours'): u (for 'up') quark which carries a charge of $\frac{2}{3}$ and a strangeness of 0; the d ('down') quark which carries a charge of $-\frac{1}{3}$ and $S = 0$; the s ('strange') quark which carries a charge of $-\frac{1}{3}$ and $S = -1$. To each quark (q) there corresponds an antiquark ($\overline{q}$), with the opposite charge and strangeness. There are two ***composition rules***:

1. Every baryon is composed of three quarks (and every antibaryon is composed of three antiquarks).

2. Every meson is composed of a quark and an antiquark.

The Pauli exclusion principle states that no two electrons can carry the same state. It was later realised that the same rule applies to all particles of half-integer spin. In particular, the exclusion principle should apply to quarks, which, as we shall see, must carry spin $\frac{1}{2}$. Now the Δ^{++}, for instance, is supposed to consist of three identical u quarks in the same state - appearing to be inconsistent with the Pauli principle. To avoid this, it was proposed that quarks not only come in three flavours, but each of these also come in three *colours* (red, green, and blue, say). To make a baryon, we simply take one quark of each colour, then the three u's in Δ^{++} are no longer identical.

Redness, blueness, and greenness are simply *labels* used to denote three new properties that, in addition to charge and strangeness, the quarks possess. A *red* quark carries one unit of redness, zero blueness, and zero greenness; its antiparticle carries minus one unit of redness, and so on.
The colour terminology has one especially nice feature: it suggests a delightfully simple characterisation of the particular quark combinations that are found in nature:

All naturally occurring particles are colourless.

That is, *either* the total amount of each colour is zero, *or* all three colours are present in equal amounts. This explains why you can't find isolated quarks, and why you can't make a particle out of two, or four quarks (for example). The only colourless combinations you can make are $q\bar{q}$ (the mesons), qqq (the baryons), and $\overline{qqq}$ (the antibaryons).

1.9 – The November Revolution

A newly discovered ψ meson was an electrically neutral, extremely heavy neutron – more than three times the weight of a proton. This particle has an extraordinarily long lifetime (on the order of 10^{-20}s opposed to 10^{-23}s – $\sim$ 1000 times longer). The ψ is a bound state of a new (fourth) quark, the c (for *charm*) and its antiquark, $\psi = (c\bar{c})$.
Eventually, fifth and sixth quarks were identified (b – bottom; t – top, respectively) along with a new heavy meson (the *upsilon*) and a new lepton (the tau, which has its own neutrino).

1.10 – Intermediate Vector Bosons (1983)

The process of beta decay is actually mediated by some exchange particle (instead of it being from a contact interaction). This mediator became known by the name *intermediate vector boson*. There are in fact *three* intermediate vector bosons, two of them charged ($W^{\pm}$) and one neutral (Z).

1.11 – The Standard Model

In the current view, all matter is made out of three kinds of elementary particles: leptons, quarks, and mediators. There are also antileptons, with all the signs reversed. The

l	Q	L_e	L_μ	L_τ
e	−1	1	0	0
ν_e	0	1	0	0
μ	−1	0	1	0
ν_μ	0	0	1	0
τ	−1	0	0	1
ν_τ	0	0	0	1

Table 1: Lepton Classification

positron, for example, carries a charge of +1 and an electron number −1.
Similarly, there are six 'flavours' of quarks, classified by charge, strangeness (S), charm (C), beauty (B), and truth (T) as well as 'upness', U, and 'downness', D.

q	Q	D	U	S	C	B	T
d	−1/3	−1	0	0	0	0	0
u	2/3	0	1	0	0	0	0
s	−1/3	0	0	−1	0	0	0
c	2/3	0	0	0	1	0	0
b	−1/3	0	0	0	0	−1	0
t	2/3	0	0	0	0	0	1

Table 2: Quark Classification

Again, all signs would be reversed on the table of antiquarks. Meanwhile, each quark and antiquark comes in three colours, so there are 36 of them in all.

Finally, every interaction has its mediator – the photon for the electromagnetic force, two W's and a Z for the weak force, the graviton (presumably) for gravity, and now the ***gluon*** for the strong force (which is exchanged between quarks in a strong process).