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DSE2T (Nuclear and Particle Physics)

Topic – Particle Physics (Part – 5)

We have already discussed part 4 of this e-report.

Now let us continue part 5 of it.

Quark Structure of Mesons:

The quarks, like the leptons are point-like fermionic particles. In other words, they have spin angular momentum of $\frac{1}{2}\hbar$. This suggests that, since mesons have integer spin, then if they are bound states of quarks, they can only consist of an even number of these particles. In fact, every known meson can be described as a bound state of two particles, namely *a quark* (q) and *an antiquark* ($\bar{q}$).

The following Table 1 shows different combinations of quarks and antiquarks to form some well known mesons.

$q\bar{q}$	Electric Charge (Q)	Strangeness (S)	Meson
$u\bar{u}$	0	0	?
$u\bar{d}$	1	0	π^+
$u\bar{s}$	1	1	K^+
$d\bar{u}$	-1	0	π^-
$d\bar{d}$	0	0	?
$d\bar{s}$	0	1	K^0
$s\bar{u}$	-1	-1	K^-
$s\bar{d}$	0	-1	$\bar{K}^0$
$s\bar{s}$	0	0	?

Table 1

Table 1 shows that a π^+ meson, which has spin zero and electric charge +1, can be described as the bound state

$$\pi^+ = u\bar{d}$$

It follows, therefore, that the π^- meson, which is the antiparticle of the π^+, can be described as the bound state

$$\pi^- = d\bar{u}$$

There are a few "?" signs in Table 1, showing some initial confusion about the nomenclature, since the π^0 meson, which is charge neutral, can, in principle, be described as a bound state of any quark and its antiquark (for example, $u\bar{u}$ or $d\bar{d}$ or $s\bar{s}$). However, other considerations, such as the fact that all three π-mesons belong to a strong-isospin multiplet, and should therefore have the same internal structure, lead to a description of the π^0 meson as

$$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

The strange mesons can similarly be described as bound states of a quark and an antiquark, where one of the constituents is strange. Thus, we can identify the following systems

$$K^+ = u\bar{s}$$

$$K^- = s\bar{u}$$

$$K^0 = d\bar{s}$$

$$\overline{K^0} = s\bar{d}$$

It is quite easy to check that not only are the charge assignments right, but even the strangeness quantum numbers work out to be correct if we assign a strangeness quantum number $S = -1$ to the s-quark. Because there are quarks with higher mass and new flavour quantum numbers, phenomenologically, on the basis of the quark model, we would also expect new kinds of mesons. Many such mesons have already been found. For example, the charge-neutral J/ψ meson, whose discovery in 1974 by independent groups headed by Samuel Ting and by Burton Richter suggested first evidence for the existence of the charm quark, can be described as a bound state of charmonium as

$$J/\psi = c\bar{c}$$

This is a normal meson, in the sense that the quantum numbers of charm add up to zero, but its decay properties cannot be explained using only the older *u*, *d* and *s* quarks. There are, of course, mesons that contain *open* charm, such as

$$D^+ = c\bar{d}$$

$$D^- = d\bar{c}$$

$$D^0 = c\bar{u}$$

$$\overline{D^0} = u\bar{c}$$

We can think of such mesons as the charm analogs of the *K* mesons, and the properties of these mesons have by now been studied in great detail. In analogy with the K^+, the D^+ meson is defined to have charm flavour of +1, which then defines the charm quantum number for the *c*-quark to be +1. There are also mesons that carry both strangeness and charm quantum numbers, two of these are denoted as

$$D_s^+ = c\bar{s}$$

$$D_s^- = s\bar{c}$$

Finally, there is also extensive evidence for hadrons in which one of the constituents is a bottom quark. For example, the *B* mesons, analogous to the *K* mesons, have structure of the form

$$B^+ = u\bar{b}$$

$$B^- = b\bar{u}$$

$$B_d^0 = d\bar{b}$$

$$\overline{B_d^0} = b\bar{d}$$

$$B_s^0 = s\bar{b}$$

$$\overline{B_s^0} = b\bar{s}$$

Quark Structure of Baryons:

Just as mesons can be thought of as bound states of quarks and antiquarks, so that baryons can also be considered as constructed out of these constituents. But because baryons carry half-integral spin angular momenta $\frac{1}{2}\hbar$ (because they are fermions), they can be formed from only an odd number of quarks. Properties of baryons are most consistent with being composed of only *three quarks*. Thus, we can think of the proton and the neutron as corresponding to the bound states

$$p = uud$$

$$n = udd$$

Similarly, the hyperons, which carry a strangeness quantum number, can be described by

$$\Lambda^0 = uds$$

$$\Sigma^+ = uus$$

$$\Sigma^0 = uds$$

$$\Sigma^- = dds$$

Also, the cascade particles, which carry two units of strangeness ($S = -2$), can be described as

$$\Xi^0 = uss$$

$$\Xi^- = dss$$

The following Table 2 shows different combinations of quarks to form some well known baryons. Since all baryons have baryon number of unity, it follows therefore that each quark must carry a baryon number of $B = \frac{1}{3}$. Furthermore, since a meson consists of a quark and an antiquark, and since an antiquark would have a baryon number $B = -\frac{1}{3}$, we conclude that mesons do not carry baryon number, which is consistent with our previous discussion.

qqq	Electric Charge (Q)	Strangeness (S)	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}, p
udd	0	0	Δ^{0}, n
uus	1	-1	Σ^{+}
uds	0	-1	Σ^{0}, Λ^{0}
uss	0	-2	Ξ^{0}
ddd	-1	0	Δ^{-}
dds	-1	-1	Σ^{-}
dss	-1	-2	Ξ^{-}
sss	-1	-3	Ω^{-}

Table 2

Colour Quantum Number:

Extending the quark model to all baryons, leads to a theoretical difficulty. From Table 2, we find that the Δ^{++} baryon, which is non-strange in nature, carries two units of positive charge and it also has spin angular momentum of $\frac{3}{2}\hbar$. Thus, we can conclude that the Δ^{++} can be described by three up (u) quarks.

$$\Delta^{++} = uuu$$

This substructure satisfies all the known quantum numbers, and, in the ground state (where there are no contributions from relative orbital waves), the three up (u) quarks can have parallel spins to provide a resultant value of $J = \frac{3}{2}$. However, the wave function for this final state, representing three identical fermions, would therefore be symmetric under the exchange of any two quarks. This is, of course, incompatible with the Pauli's exclusion principle, which requires a wave function containing identical fermions to be totally antisymmetric. It would appear, therefore, that the quark model solely cannot describe the Δ^{++}. An interesting resolution can be attained if it is assumed that all quarks carry an additional internal quantum number, and that the final state in is, in fact, antisymmetric in the space corresponding to this new quantum number.

This additional degree of freedom is referred to as *colour*, and it is believed that each of the quarks comes in three different colours. Namely, the quark multiplets take the form

$$\begin{pmatrix} u^a \\ d^a \end{pmatrix}, \begin{pmatrix} c^a \\ s^a \end{pmatrix} \text{ and } \begin{pmatrix} t^a \\ b^a \end{pmatrix}$$

where $a =$ red, blue or green is the colour quantum number.

At this point of our development, colour can be regarded as merely a new quantum number needed for phenomenological reasons for understanding the substructure of hadrons. However, it can be shown that, *colour is to the strong interaction* what charge is to the electromagnetic force, namely the source of the respective fields. Hadrons do not appear to carry any net colour, and therefore correspond to bound states of quarks and antiquarks of zero total colour quantum number, or simply stated, hadrons are colour-neutral bound states of quarks. Under the interchange of any two quarks, the colour singlet wave function of three quarks changes sign, while that of a quark-antiquark colour singlet does not. This hypothesis leads to an excellent description of all known baryons as bound states of three quarks, and of mesons as bound states of quark-antiquark pairs. In particular, it also explains the structure of the Ω^- baryon which has a strangeness of $S = -3$ and spin angular momentum of $\frac{3}{2}\hbar$, and corresponds to the ground state of three strange quarks

$$\Omega^- = sss$$

Gauge Bosons:

It is important to note that local invariance necessarily leads to the introduction of *gauge potentials*, such as the vector potential in electromagnetic interactions. When these potentials are quantized, they provide the carriers of the force, otherwise known as *gauge particles* or *gauge bosons*. Thus, the photon is the carrier of the electromagnetic interaction, or its gauge boson. All the gauge bosons have spin $J = 1$, and the number of gauge bosons associated with any symmetry reflects the nature of that symmetry group. There are three gauge bosons associated with the weak interactions, and they are known as the W^+, W^-

and Z^0 bosons (these were discovered independently in 1983 by Carlo Rubbia and collaborators and Pierre Darriulat and collaborators at the antiproton-proton collider at the CERN Laboratory outside of Geneva, Switzerland). For the strong interactions, there are eight gauge bosons, and all are referred to as *gluons* (these are the same gluons we have been discussing in connection with the substructure of the nucleon). The gluons, or the gauge bosons of colour symmetry, are electrically neutral, but carry the colour quantum number. This is in contrast to the photon, which is the carrier of the force between charged particles, but does not itself carry electric charge. The gauge particles for various interactions are listed in the following Table 3.

Type of Interaction	Range	Mediator or Gauge Particle
Gravitational	Long	Graviton
Weak	Short	W^+, W^- and Z^0 bosons
Electromagnetic	Long	Photon
Strong	Short	Gluon

Table 3

Reference(s):

Introduction to Elementary Particles, D. J. Griffiths, John Wiley & Sons

Introduction to Nuclear and Particle Physics, A. Das & T. Ferbel, World Scientific

(All the figures have been collected from the above mentioned references)