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DSE2T (Nuclear and Particle Physics)

Topic – Particle Physics (Part – 2)

We have already discussed part 1 of this e-report.

Now let us continue part 2 of it.

Strangeness (S). In early studies of cosmic ray showers, it was found that certain particles, which have since been identified with K -mesons and the Σ and Λ^0 baryons, were produced strongly (that means, with large cross sections), but had lifetimes characteristic of weak interactions, namely $\sim 10^{-10}$ sec. These particles were always produced in pairs, for example, a K in association with either a Σ or Λ^0. This type of production mechanism is called as *associated production*. All this was certainly surprising, and led to an idea that a new quantum number might be associated with such particles. When specific reactions, such as

$$\pi^- + p \to K^0 + \Lambda^0$$

were studied along with the decay of Λ^0 or K^0 given as

$$K^0 \to \pi^+ + \pi^-$$

$$\Lambda^0 \to p + \pi^-$$

it was observed that the Λ^0 was always produced in association with a K^0 and never with just a π^0. The Λ^0 was also observed to be produced in association with a K^+, but never with a K^-, the reaction is given by

$$\pi^- + p \to K^+ + \pi^- + \Lambda^0$$

Similarly, for the reaction where Σ^+ and K^+ were produced in association

$$\pi^+ + p \to K^+ + \Sigma^+$$

it was observed that the Σ^+ was always produced in association with a K^+ and never with just a π^+. Here Σ^+ and K^+ subsequently decay as

$$\Sigma^+ \rightarrow \pi^+ + n$$

$$K^+ \rightarrow \pi^+ + \pi^0$$

The production cross sections for reactions such as those given before revealed that these production processes were strong (strong interaction). The subsequent decays of these particles were also studied, and revealed that the decay processes are rather weak. This was a real puzzle, and it was not observed at that time. That's why this type of particles were called as *strange particles*.

The puzzle of *associated production* was clarified by Murray Gell-Mann and Abraham Pais, who proposed that these particles carried a new additive quantum number, which they called *strangeness* (S), which is conserved in strong production processes, but is violated in weak decays. All the ordinary mesons and baryons (as well as the photon) were assumed to be non-strange, and were assigned as $S = 0$. Thus, in any strong associated production reaction with the initial state having no strangeness, the total strangeness of the particles in the final-state must also add up to zero. That explains the cause of associated production. From the analysis of such reactions, it was deduced that the strangeness of the K^+ and K^0 must be opposite to that of the Σ^+, Σ^0, Σ^- and Λ^0. In fact the relation between strangeness (S) and charge (Q) for the hadrons can be shown as a Meson Octet (Fig. 1) and Baryon Decuplet arrangement (Fig. 2).

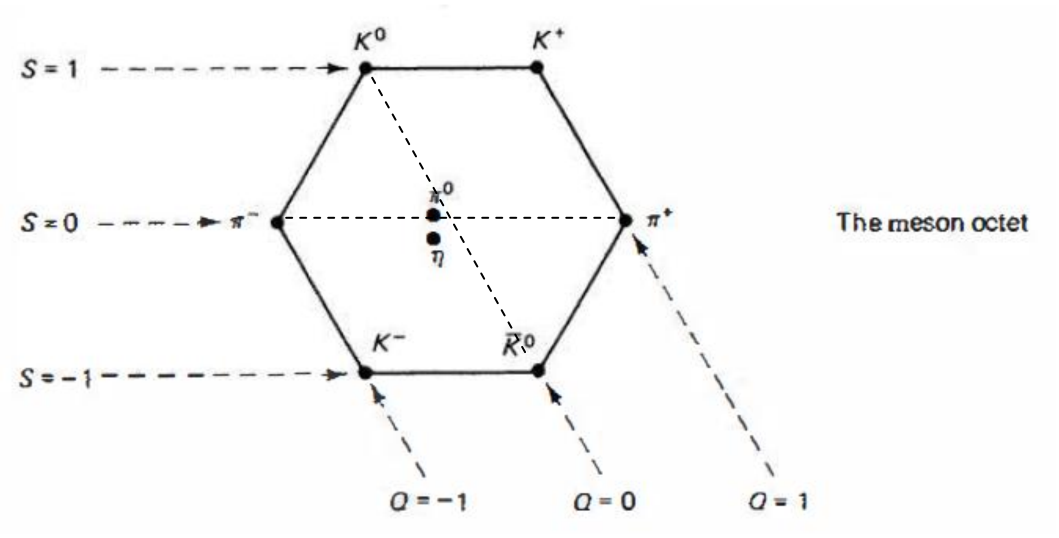

Fig. 1

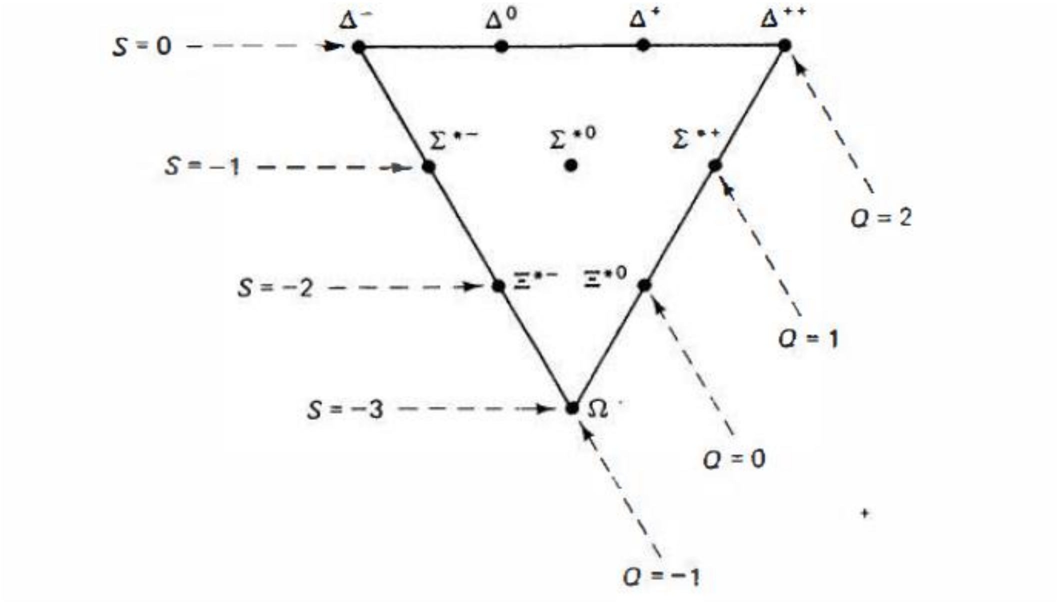

Fig. 2

From the two arrangements we get to know that the sigma particles Σ^+, Σ^0, Σ^- can given strangeness $S = -1$, cascade particles Ξ^0 and Ξ^- can be assigned the strangeness $S = -2$, omega particle Ω^- can assigned $S = -3$ and the $\bar{K}^0$ and K^- have $S = -1$. The latter assignment is consistent with our identification of the K^- and $\bar{K}^0$ as antiparticles of the K^+ and K^0 respectively.

It is important to note that weak decays of hadrons do not conserve strangeness. Consequently, if we assume strangeness to be conserved only in strong and electromagnetic interactions, it then follows that we cannot assign unique strangeness quantum numbers to leptons.

Isospin or Isotopic Spin (*I*). The proton and the neutron are two baryons with spin $\frac{1}{2}$ and are essentially degenerate in their mass. In fact, as we already indicated they are quite similar in their nuclear properties, except the fact that the proton has a positive charge whereas the neutron is electrically neutral. Correspondingly, their electromagnetic interactions are quite different and their magnetic dipole moments have opposite sign. It has been known for a long time that the strong force does not depend on the charge of a particle. In fact, studies of mirror nuclei have demonstrated that the strong binding forces between *p-p*, *p-n* and *n-n* are basically the same.

Therefore the strong interactions do not distinguish between a proton and a neutron. Consequently, if we imagine a world where only the strong force is present and the weak and electromagnetic forces are cut off, then in such a world a proton would be indistinguishable from a neutron. In such a world, we can think of the proton and the neutron as *two orthogonal states* of the same particle (called as *nucleon*), and can write the states for the neutron and proton as

$$p = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ and } n = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

This language is very similar to that used in discussing the "spin up" and the "spin down" states of a spin $\frac{1}{2}$ particle, which are also indistinguishable in the absence of any interaction that breaks rotational symmetry (a magnetic field, for example). The two spin states will be degenerate in energy until we apply an external magnetic field, which picks out a preferred direction in space, and removes the degeneracy of the two states. In much the same way, we can think of the proton and the neutron as being degenerate in mass because of some symmetry of the strong force, and we call this symmetry the *isotopic spin* or in short, *isospin* symmetry. In reality, the presence of electromagnetic and weak forces breaks this symmetry, lifts the degeneracy in the masses, and allows one to distinguish between a neutron and a proton. Therefore, in the absence of electromagnetic and weak forces, we can think of the three pions as corresponding to different states of one particle, the π meson, and we can represent the pion states as

$$\pi^+ = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \pi^0 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \text{ and } \pi^- = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

In fact, this discussion can be extended to all the known hadrons, which can be classified into multiplets corresponding to some quantum number very much like the spin quantum number. We will refer to this quantum number as the strong isotopic spin or strong isospin (I), and its conservation suggests the invariance of the strong Hamiltonian under isospin transformations. These transformations correspond to rotations very much like those that occur for spin, but the rotations are in an internal Hilbert space and not in space-time. The isospin quantum number is found to be conserved in strong interactions (it is a symmetry of the strong force). However, it does not appear to be conserved in electromagnetic or weak processes.

Table 1 summarizes the strong isospin quantum numbers of different hadrons, as determined from scattering experiments. The assignment for the third-component or projection of the isospin chosen in the table is such that, in any given isospin multiplet, a particle with a *larger positive charge* has a higher value of the isospin projection. We have also denoted the projection as I_3 instead of the conventional notation I_z, in order to emphasize that isospin is not a space-time symmetry.

Hadron name	I	I_3
p	$\frac{1}{2}$	$+\frac{1}{2}$
n	$\frac{1}{2}$	$-\frac{1}{2}$
π^+	1	$+1$
π^0	1	0
π^-	1	-1
Σ^+	1	$+1$
Σ^0	1	0
Σ^-	1	-1
Λ^0	0	0
η^0	0	0
Ω^-	0	0
K^+	$\frac{1}{2}$	$+\frac{1}{2}$
K^0	$\frac{1}{2}$	$-\frac{1}{2}$
$\bar{K}^0$	$\frac{1}{2}$	$+\frac{1}{2}$
K^-	$\frac{1}{2}$	$-\frac{1}{2}$
Ξ^0	$\frac{1}{2}$	$+\frac{1}{2}$
Ξ^-	$\frac{1}{2}$	$-\frac{1}{2}$

Table 1

Gell-Mann - Nishijima Relation:

The assignment of the strangeness quantum number (S) and the other choices (for example, I or I_3) made earlier, may appear to be rather adhoc. In fact, these were made originally with the phenomenological observation in mind that the electric charge (Q) of a hadron can be related to its other quantum numbers through the *Gell-Mann - Nishijima Relation* given as

$$Q = I_3 + \frac{B+S}{2} = I_3 + \frac{Y}{2}$$

where $Y = B + S$ is called as the *hypercharge*. We summarize the quantum numbers of several typical long-lived hadrons in Table 2. These are all consistent with Gell-Mann - Nishijima Relation.

Hadron name	Q	I_3	B	S
p	$+1$	$+\frac{1}{2}$	$+1$	0
n	0	$-\frac{1}{2}$	$+1$	0
π^+	$+1$	$+1$	0	0
π^0	0	0	0	0
π^-	-1	-1	0	0
Σ^+	$+1$	$+1$	$+1$	-1
Σ^0	0	0	$+1$	-1
Σ^-	-1	-1	$+1$	-1
Λ^0	0	0	$+1$	-1
η^0	0	0	0	0
Ω^-	-1	0	$+1$	-3
K^+	$+1$	$+\frac{1}{2}$	0	$+1$
K^0	0	$-\frac{1}{2}$	0	$+1$
$\bar{K}^0$	0	$+\frac{1}{2}$	0	-1
K^-	-1	$-\frac{1}{2}$	0	-1
Ξ^0	0	$+\frac{1}{2}$	$+1$	-2
Ξ^-	-1	$-\frac{1}{2}$	$+1$	-2

Table 2

With the subsequent discovery of new particles with new flavour quantum numbers such as *charm* and *bottom*, in addition to strangeness, the Gell-Mann - Nishijima relation has been generalized to include these as well. In the expanded relation, the hypercharge is denned to be the sum of the baryon number, strangeness and all the new flavour quantum numbers. With this modification, the original relation holds for all hadrons. Since charge and isospin are conserved in strong interactions, it follows that the generalized hypercharge is also conserved in such processes. In fact, each of the flavours is conserved independently in strong interactions.

Quantum Number Violations:

As we have seen, all quantum numbers appear to be conserved in strong processes, however, some are violated in electromagnetic and weak interactions, and we will discuss a few illustrative examples of these.

(a) In Weak Interactions. There are three kinds of weak processes in nature, which can be classified as (a) hadronic decays, where only hadrons are present in the final state, (b) semi-leptonic processes, where both hadrons and leptons are present and (c) leptonic processes, where only leptons are present. Since most of the strong quantum numbers are not defined for leptons, it is not meaningful to discuss their violation in leptonic processes. Furthermore, even in the case of the semi-leptonic processes, we can only speak about the conservation or the violation of quantum numbers between the initial and the final hadronic states. Keeping this in mind, let us now examine some typical reactions.

Consider the following decays of hadrons into other hadrons

$$\Lambda^0(I_3 = 0, S = -1) \to p(I_3 = \tfrac{1}{2}, S = 0) + \pi^-(I_3 = -1, S = 0)$$

$$K^0(I_3 = -\tfrac{1}{2}, S = 1) \to \pi^+(I_3 = 1, S = 0) + \pi^-(I_3 = -1, S = 0)$$

$$\Xi^-(I_3 = -\tfrac{1}{2}, S = -2) \to \Lambda^0(I_3 = 0, S = -1) + \pi^-(I_3 = -1, S = 0)$$

We see that both isospin and strangeness are violated in these decays, and that a selection rule for such violations can be summarized by $|\Delta S| = 1$, $|\Delta I_3| = \frac{1}{2}$.

Now we examine only a few examples to bring out the essential features of semi-leptonic decays and emphasize that we consider only changes in the quantum numbers of initial and final state hadrons.

$$n(I_3 = -\tfrac{1}{2}, S = 0) \to p(I_3 = \tfrac{1}{2}, S = 0) + e^- + \overline{\nu_e}$$

$$\pi^-(I_3 = -1, S = 0) \to \mu^- + \overline{\nu_\mu}$$

$$\pi^+(I_3 = 1, S = 0) \to \pi^0(I_3 = 0, S = 0) + e^+ + \nu_e$$

$$\Lambda^0(I_3 = 0, S = -1) \to p(I_3 = \tfrac{1}{2}, S = 0) + e^- + \overline{\nu_e}$$

Here the first kind of process has no change in the strangeness flavour of hadrons. The strangeness-conserving semi-leptonic processes therefore satisfy

$$|\Delta S| = 0,\ |\Delta I_3| = 1 \text{ and } \Delta I = 1$$

The second class of semi-leptonic decays do not conserve strangeness. Consequently, these decays are also known as strangeness-changing processes, and for these we find $|\Delta S| = 1$, $|\Delta I_3| = \frac{1}{2}$ and $\Delta I = \frac{1}{2}$ and $\frac{3}{2}$.

(b) In Electromagnetic Interactions. Let us also consider several samples of electromagnetic decays. Again, since strong quantum numbers cannot always be defined for a photon, the meaningful quantity to analyze is the change in the quantum numbers of the hadrons.

$$\pi^0(I_3 = 0, S = 0) \to \gamma + \gamma$$

$$\eta^0(I_3 = 0, S = 0) \to \gamma + \gamma$$

$$\Sigma^0(I = 1, I_3 = 0, S = -1) \to \Lambda^0(I = 0, I_3 = 0, S = -1) + \gamma$$

This shows that strangeness is conserved in electromagnetic processes, while total isospin is not. In fact, these processes are characterized by

$$|\Delta S| = 0,\ |\Delta I_3| = 0 \text{ and } \Delta I = 1 \text{ and } 0$$

Neutrino:

In a beta (β)-decay process, a nucleus with an over abundance of neutrons (i.e., with a value of $\frac{N}{Z}$ greater than that for stable nuclei) can transform to a more stable nucleus by emitting an electron and the transformation can be denoted by

$$X_Z^A \to Y_{Z+1}^A + e^-$$

Because only the electron and the recoiling daughter nucleus were initially observed in β-decay, the process was initially assumed to be a two-body disintegration, very much like α-decay. However, these electrons are emitted with a continuous spectrum of energies, with most values lying well below that predicted by energy conservation in two-body decays. When this was first observed, it appeared to threaten the most popular conservation laws in physics, namely energy conservation. In addition, a consideration of the change in angular momentum in β-decay processes reveals that angular momentum could not be conserved if the decays produced only two particles in the final state.

To extricate science from this abyss, Pauli proposed that an additional particle, one that was difficult to detect, was emitted in β-decay. Conservation of electric charge required this particle to be electrically neutral, just like the neutron and the photon. This particle was called as *Neutrino* and denoted as ν. Obviously, this would explain why it was so hard to detect this particle. Neutrino does not interact readily with matter, and this is the main reason why it is so difficult to observe. Because the maximum energies for electrons emitted in β-decay corresponded to the disintegration energy of the nucleus, it meant that neutrino had to be essentially massless. Furthermore, if it were to restore the conservation of angular momentum, then it would have to be a fermion with spin angular momentum $\frac{\hbar}{2}$.

The antiparticle of neutrino is known as the *antineutrino* ($\bar{\nu}$). Since both the neutrino and the antineutrino are electrically neutral, an interesting question is what specific property distinguishes them from each other. Unlike neutron, the neutrino is an essentially massless point particle, without structure and it has neither nucleon number nor a magnetic dipole moment to distinguish between particle and antiparticle. Experiments on β-decay indicate that neutrinos that accompany positrons are left-handed, whereas the ones that accompany electrons are right-handed, where by left-handed we mean that the particle has its spin pointing opposite to its momentum. Consequently, the handedness is one of the distinguishing characteristics between a neutrino and its antiparticle.

The three types of neutrinos (ν_e or electron neutrino, ν_μ or muon neutrino and ν_τ or tauon neutrino) are also known to be distinct from one another. For example, when neutrinos produced in a decay such as $\pi^+ \rightarrow \mu^+ + \nu_\mu$ are allowed to interact with matter, they never produce charged leptons other than negative muons. That is

$$\nu_\mu + X_Z^A \rightarrow Y_{Z+1}^A + \mu^-$$

Similarly ν_e interacting with matter always produce electrons, given by

$$\nu_e + X_Z^A \rightarrow Y_{Z+1}^A + e^-$$

This family structure for leptons and their neutrinos plays a major role in constructing theories of fundamental interactions.

This concludes part 2 of this e-report.

The discussion will be continuing in the part 3 of this e-report.

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)