Review

Two alternative versions of strangeness

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(Contributed by Kazuhiko NISHIJIMA, M.J.A.)

Abstract: The concept of strangeness emerged from the low energy phenomenology before the entry of quarks in particle physics. The connection between strangeness and isospin is rather accidental and loose and we recognize later that the definition of strangeness is model-dependent. Indeed, in Gell-Mann's triplet quark model we realize that there is a simple alternative representation of strangeness. When the concept of generations is incorporated into the quark model we find that only the second alternative version of strangeness remains meaningful, whereas the original one does no longer keep its significance.

Keywords: strangeness, Sakata model, quark model, algebra of weak currents, generation

1. Introduction

In the late forties the so-called V particles were discovered, and the investigation of their properties led us to the establishment of the concept of flavors and generations later. As we now know; particles of higher (second and third) generations decay quickly into those of the first generation so that the former could not be observed unless they were produced by accelerators or cosmic rays. We realize, therefore, that we are normally surrounded by particles of the first generation alone. This set-up provided us with the boundary condition for the natural laboratories in which experimental studies of V particles had been performed.

In the early fifties cosmic rays were the main tool for studying V particles, but there was a technical cut-off for cosmic ray energies in order to observe their decay tracks within the cloud chambers. Thus this constraint made it impossible to observe particles of higher flavors except for the V or strange particles, and at that time our hadronic world consisted of hadrons of the first generation and strange particles.

In the first half of this article our reasoning of the structure of the hadronic world is developed on the above assumption that we may call low energy phenomenology. Then, in the second half we introduce the quark model and show how the properties of strange particles in low-energy phenomenology can be accounted for in terms of this model. The contents of this article are organized to realize the strategy described above.

In Sec. 2 we introduce charge independence (CI) which is one of the most important symmetries in hadron physics and interpret properties of V particles on the basis of this symmetry.

The constituents of matter are hadrons and leptons and in Sec. 3 we focus our eyes on leptons. From the experimental studies of leptons it had been suggested that there would be two kinds of leptons, one belonging to the electron family and the other to the muon family. This was an important forerunner of the concept of generations that would be clarified later in the quark model.

In Sec. 4 we advance our considerations to various models of hadrons by Fermi and Yang, by Sakata and by Gell-Mann. It is at this level that we find two alternative representations of strangeness, one for low energy phenomenology and the other for the quark models.

In Sec. 5 we concentrate our attention on the algebraic properties of weak currents that are the richest source of information about the family structure of elementary particles. Then we lift the energy constraint imposed on low energy phenomenology so as to introduce the charm quark that

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changes our interpretation of strangeness completely.

2. Charge independence and V particles

Charge independence (CI) is one of the most important concepts in particle physics. It is an old symmetry recognized in the early days of nuclear physics but persisted in playing a major role in the gauge theory of electroweak interactions.

From elucidation of the level structure of mirror nuclei it had been recognized that the proton-proton (pp) and neutron-neutron (nn) interactions are approximately equal except for the difference due to Coulomb interactions. This property was called charge symmetry. Furthermore, from the pp and pn scattering experiments at low energies it had also been recognized that the pp and pn interactions are approximately equal. Thus, in the angular momentum states not excluded by the Pauli principle we have an approximate equality of nuclear potentials:

$$V_{pp} \approx V_{pn} \approx V_{nn}.$$
 [2.1]

The independence of the two-body nuclear forces on the nuclear charge is called $\text{CI.}^{1)-3)}$

This symmetry corresponds to the invariance of the nuclear system under the following SU(2) transformation:

$$\binom{p'}{n'} = U\binom{p}{n}, \qquad [2.2]$$

where U is unitary and unimodular, namely,

$$U^{\dagger}U = UU^{\dagger} = 1, \qquad [2.3]$$

det
$$U = 1.$$
 [2.4]

Since this group of transformations is isomorphic to the group of space rotations, we may introduce isospin I corresponding to the angular momentum J.

I is a vector in charge space with three components I_1 , I_2 and I_3 satisfying the commutation relations

$$[I_a, I_b] = i\epsilon_{abc}I_c, \qquad [2.5]$$

which are identical with those of J. CI is an approximate symmetry since the Coulomb interactions and the proton-neutron mass difference break this symmetry. It is important to realize, however, that the third component I_3 is conserved in strong and electromagnetic interactions and is

Table 1.

	nucleon doublet		pion triplet		
	р	n	π^+	π^0	π^{-}
I_3	$\frac{1}{2}$	$-\frac{1}{2}$	1	0	-1
Q	e	0	e	0	-e

Table	2.
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	(3,3) resonance			
	Δ^{++}	Δ^+	Δ^0	Δ^{-}
I_3	$\frac{3}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{3}{2}$
Q	2e	e	0	-e

violated only in weak interactions.

The nuclear forces are mediated by the pion or the Yukawa meson so that the pion-nucleon interactions must also respect this symmetry. Kemmer formulated such a symmetrical theory⁴ accepting Pauli's suggestion in 1936.

Then we can pick out the most fundamental charge multiplets in Table 1.

We can give many other multiplets but here we shall choose just one example in Table 2.

The (3,3) resonance states are realized in pionnucleon scattering and they carry $I = J = \frac{3}{2}$.

In these examples we find by comparing the charges and the third components of the closest neighbors the following relationship:

$$\Delta Q = e \Delta I_3. \tag{2.6}$$

By integrating this difference equation we obtain

$$Q = e\left(I_3 + \frac{Y}{2}\right), \qquad [2.7]$$

where Y is a constant of integration called hypercharge. Each multiplet carries a definite hypercharge and we recognize later that it is an important quantum number in the gauge theory of electroweak interactions.

Now we switch to V particles. In the late forties Rochester and Butler⁵⁾ observed two new events in the cloud chamber operated at the sea level. They were the celebrated V particles named according to the shapes of the decay tracks of these particles. This was indeed the dawn of the flavor physics developed later. Soon it became clear that V particles are produced at high altitude and decay quickly. Therefore, it is more effective to go up to mountains to observe them before they decay, and for this reason the Caltech group⁶⁾ went up to the White Mountain and the Manchester group⁷⁾ went up to Pic du Midi to observe several tens of V events. There were also some early contributions from the French group, including Leprince-Ringuet and others, but they were not well recognized since their work was not easily accessible to us. We shall skip the historical details, but we stress the experimental findings that V particles are produced by strong interactions but decay by weak interactions with the lifetimes of the order of 10^{-10} sec. Then a question was raised of why V particles do not decay through strong interactions. In order to avoid strong decays there must be a selection rule to forbid them.

In response to this question a number of authors⁸⁾⁻¹⁰⁾ published their theories in 1951 in a meeting held at the University of Tokyo. There was one aspect common to all these theories. In 1952 Pais came up with a similar idea.¹¹ All of these authors assumed that V particles are produced in pairs by strong interactions. Then we may introduce a sort of parity tentatively called V parity P_V and assume that P_V is conserved in strong and electromagnetic interactions but is violated eventually in the weak interactions just like space parity. Then let us postulate that V particles carry negative V parity whereas stable or semi-stable hadrons around us carry positive one.

Under these assumptions it is clear that V particles are produced always in pairs by strong interactions and decay through weak interactions since the V parity has to change its sign in decay processes. Later we shall find a close connection between this pair production mechanism and the quark model. Unfortunately, it was difficult to confirm this pair production hypothesis by cosmic ray experiments since it was not easy to observe two decay tracks simultaneously in one picture.

An experimental confirmation of this hypothesis came from the Cosmotron experiment at Brookhaven in 1953. This was certainly shocking to cosmic ray physicists and in July 1953 the Bagnères de Bigorre Conference on cosmic rays had been held, and C. F. Powell made an alarming speech there: "Gentlemen, we have been invaded. ... the accelerators are here." It was a critical time for cosmic ray physicists and some of them switched their experimental means from cosmic rays to accelerators since the experimental conditions can be controlled artificially in the latter and the intensity of particle beams is much higher in the latter than in the former.

The following two processes had been observed by the Cosmotron experiment:¹²⁾

$$\pi^- + p \to \Lambda^0 + K^0, \qquad [2.8]$$

$$\pi^- + p \to \Sigma^- + K^+.$$
 [2.9]

There are various V particles and they are distinguished by proper names. Here, Λ^0 and Σ^- are baryons and K^+ and K^0 are heavy mesons. The two processes alone clearly confirm the pair production hypothesis.

There had been still some problems left unsolved.

- 1. Observed charged K mesons were almost exclusively positive and the problem then was how to interpret this positive excess.^{13),14)}
- A new baryon Ξ[−] which undergoes cascade decays was discovered.¹⁵⁾ It decays in two steps as

$$\Xi^- \to \Lambda^0 + \pi^-, \Lambda^0 \to p + \pi^-. \qquad [2.10]$$

The problem was to assign a proper V parity to Ξ^- . If it is positive it would decay quickly into $n + \pi^-$, and if it is negative it would decay into $\Lambda^0 + \pi^-$ by strong interactions. Thus, the meta-stability of Ξ^- cannot be accounted for in terms of the multiple quantum number P_V alone.

For the resolution of these questions we shall introduce an additive quantum number with the help of CI. For this purpose we shall check the hypercharges of various hadrons.

$$Y = 1 \quad \text{for } (\mathbf{p}, \mathbf{n}),$$

$$Y = 0 \quad \text{for } (\pi^+, \pi^0, \pi^-),$$

$$Y = 1 \quad \text{for } (\Delta^{++}, \Delta^+, \Delta^0, \Delta^-).$$

[2.11]

We recognize that the hypercharge in these cases agrees with the baryon number B, namely,

$$Y = B. [2.12]$$

Next we examine strange baryons. Λ^0 seems to be a charge singlet so that we assign $I = I_3 = 0$ to Λ^0 , then the formula [2.7] yields

$$Y = 0 \quad \text{for } \Lambda^0. \tag{2.13}$$

Since B = 1 for Λ^0 the formula [2.12] does not hold and we introduce the difference between Y and B Nakano and the present author^{16),17)} called S the η charge, but Gell-Mann¹⁸⁾ called it strangeness and this naming persisted. Then we find

$$S = -1 \quad \text{for } \Lambda^0.$$
 [2.15]

The strangeness S is equal to zero for all the old hadrons obeying [2.12].

The production process [2.8] takes place through strong interactions so that we can apply conservation of I_3 , namely,

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

 $I_3 = -1 + \frac{1}{2} = 0 + \left(-\frac{1}{2}\right).$ [2.16]

Thus we find $I_3 = -\frac{1}{2}$ for K^0 and consequently $I_3 = \frac{1}{2}$ for its antiparticle \overline{K}^0 . Then we recognize

$$\bar{K}^0 \neq K^0.$$
 [2.17]

In the case of neutral bosons so far known, such as γ and π^0 , antiparticles are identical with the original particles so that this example gave us a strange feeling. Then, K^0 and \bar{K}^0 cannot belong to the same charge multiplet, but they belong to two separate multiplets as shown in Table 3.

In this case S = 1 for (K^+, K^0) and S = -1 for (\overline{K}^0, K^-) .

Then by studying the process [2.9] we find that Σ^- carries $I_3 = -1$, B = 1, S = -1, and it is a member of a charge triplet in Table 4.

For Ξ^- we do not know its partners, but we assume that it is a member of a charge doublet in order to avoid extraneous complications. It is shown in Table 5.

Table 3.

	K doublet		\bar{K} doublet	
	K^+	K^0	$ar{K}^0$	K^{-}
I_3	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$
Q	e	0	0	-e

Table 4.

		Σ triplet		
	Σ^+	Σ^0	Σ^{-}	
I_3	1	0	-1	
Q	е	0	-e	

Table 5.

	Ξ doublet	
	Ξ^0	Ξ^-
I_3	$\frac{1}{2}$	$-\frac{1}{2}$
Q	0	-е

In this case we find S = -2.

The quantum numbers Q, I_3 and B are conserved in strong and electromagnetic interactions and so is S, but in the decay processes S is not necessarily conserved and we postulate a selection rule for S in weak processes, namely, $\Delta S = 0, \pm 1$ which is illustrated by

(i)
$$\Delta S = 0$$
 : $n \to p + e^- + \bar{\nu}$, [2.18]

(*ii*)
$$\Delta S = \pm 1$$
 : $\Lambda^0 \to p + \pi^-$. [2.19]

Later we shall find a theoretical ground for them based on the quark model.

Now we are ready to resolve the problems that could not be accounted for on the basis of the multiple quantum number P_V alone.

- 1. As we have already seen all the strange baryons carry negative strangeness. If Kmesons are produced in association with the excitation of nucleons into strange baryons the K mesons should carry positive strangeness as is clear in the processes [2.8] and [2.9]. Thus at such low energies only K^+ of positive S can be produced thereby excluding K^- of negative S. There are processes in which K^- mesons are produced but the threshold energies are much higher and in this way we can understand the reason for the positive excess of K mesons.
- 2. The selection rule [2.19] forbids the decay $\Xi^- \to n + \pi^-$ so that [2.10] is the only possible weak decay mode for Ξ^- . Apparently P_V is related to S by

$$P_V = (-1)^S.$$
 [2.20]

3. Two neutrinos and two families of leptons

In the preceding section we have discussed the nature of hadrons in connection with CI. Matter consists of hadrons and leptons, however, so that it is also important to clarify the properties of leptons. They do not interact strongly and they have been studied mainly through weak interactions. The leptons known in the fifties had been the electron (e), the muon (μ) and the neutrino (ν) .

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Experimentally many processes were known to be forbidden and in order to account for the selection rules Konopinski and Mahmoud¹⁹⁾ introduced a hypothesis of the lepton number conservation in 1953. They postulated that e^- , μ^+ and ν be leptons and e^+ , μ^- and $\bar{\nu}$ be antileptons. Assuming that the neutrino is massless we decompose it into the right-handed and the left-handed components as $\nu = \nu_R + \nu_L$, then the lepton number à la Konopinski and Mahmoud is given by

$$l_{KM} = n(e^{-}, \mu^{+}, \nu_{R}, \nu_{L}) - n(e^{+}, \mu^{-}, \bar{\nu}_{R}, \bar{\nu}_{L}), \quad [3.1]$$

where n denotes the particle number.

Later in 1957 Lee and Yang²⁰⁾ proposed an alternative definition of the lepton number by

$$l_{LY} = n(e^{-}, \mu^{-}, \nu_L, \bar{\nu}_L) - n(e^{+}, \mu^{+}, \nu_R, \bar{\nu}_R). \quad [3.2]$$

These definitions have been modified from the original version so as to comply with the later experiments. It is interesting to recognize that conservation of both types of lepton numbers seem to be consistent with experiments.

Then in 1957 the present author²¹ assumed that both versions of the lepton number are separately conserved and took their sum and difference to find new quantum numbers, namely,

$$N_{ef} = n(e^{-}, \nu_L) - n(e^{+}, \bar{\nu}_R), \qquad [3.3]$$

$$N_{mf} = n(\mu^{-}, \bar{\nu}_L) - n(\mu^{+}, \nu_R), \qquad [3.4]$$

where N_{ef} denotes the number of leptons belonging to the electron family since it does not depend on the number of muons. Similarly, N_{mf} denotes the number of leptons belonging to the muon family. Now we may change the notation of the neutrinos to clarify the two family structure of leptons as

$$\nu_L \to \nu_e, \ \bar{\nu}_R \to \bar{\nu}_e, \ \bar{\nu}_L \to \nu_\mu, \ \nu_R \to \bar{\nu}_\mu, \quad [3.5]$$

and call ν_e and ν_{μ} as the electron-neutrino and the muon-neutrino, respectively, and reexpress [3.3] and [3.4] in the following form:

$$N_{ef} = n(e^{-}, \nu_e) - n(e^{+}, \bar{\nu}_e), \qquad [3.6]$$

$$N_{mf} = n(\mu^{-}, \nu_{\mu}) - n(\mu^{+}, \bar{\nu}_{\mu}).$$
 [3.7]

In this way we find that leptons are divided into two families, the electron family and the muon family and they are separately conserved. The family concept for leptons has been generalized to generations by accommodating hadrons (quarks) much later. A similar proposal was made also by Schwinger²²⁾ independently. In 1962 the existence of two neutrinos was confirmed by the Columbia group²³⁾ by using the AGS machine at the Brookhaven National Laboratory.

A neutrino beam is generated by decay in flight of pions and eventually of kaons. This beam consists predominantly of muon-neutrinos. They are produced by 15 GeV protons striking a Be target and the resulting flux of particles strikes a 13.5 m thick iron shield wall at a distance of 21 m from the target. Neutrino interactions are observed in a 10 ton Al spark chamber located behind this shield. After subtracting possible backgrounds they have concluded that practically only muons were produced. If there were only one kind of neutrinos, electrons would have been observed with comparable rates. Thus the most plausible explanation for the absence of electrons is that the neutrino coupled to the muon and produced in $\pi - \mu$ decay is different from the one coupled to the electron and produced in nuclear β decay. This is precisely the prediction of the hypothesis of two neutrinos.

4. Models of hadrons

As the entry of hadrons discovered by accelerators increased rapidly it was important to make a distinction between elementary and composite particles. For that purpose attempts have been made to pick out basic hadrons of which all other hadrons are made.

- 1. The first attempt had been made by Fermi and Yang²⁴) before the wide recognition of strange particles, to compose all the hadrons of nucleons and antinucleons by regarding them as the basic elementary particles. In particular, the newly discovered Yukawa meson or pion was considered to be composed of a nucleon and an anti-nucleon. Thus p and n are the basic particles in this model.
- 2. After the discovery of strange particles Sakata²⁵⁾ modified their model by adding Λ to the set of basic particles. Thus p, n and Λ form the Sakata triplet. As a natural extension of CI or the SU(2) symmetry based on the isospin doublet (p,n), Ikeda, Ogawa and Ohnuki²⁶⁾ introduced the SU(3) symmetry for the Sakata triplet (p,n, Λ). Once a symmetry is introduced we can study the multiplet structure of the composite hadrons. Let t represent one of the fundamental triplet (p,n, Λ), then



Fig. 1. Pseudoscalar meson octet.

low-lying bosons are bound states of t and \bar{t} . Corresponding representations of $t\bar{t}$ are given by

$$\mathbf{3} \times \mathbf{\bar{3}} = \mathbf{8} + \mathbf{1}.$$
 [4.1]

Hence we obtain an octet representation and eventually a singlet representation of bosons. Each member of this octet is distinguished by (I_3, I, Y) . For instance, for the pseudoscalar mesons the octet is given by Fig. 1.

The prediction of the isospin singlet η^0 was considered to be a success. We get similar results for vector mesons. However, the fundamental triplet alone cannot cover the members of baryons and this causes a lot of troubles. Experimentally it is favorable to assign an octet representation to baryons as shown in Fig. 2.

Furthermore, we find no hadrons belonging to a triplet representation among those observed experimentally. It is not possible to introduce the baryon octet shown above as long as we stick to the Sakata model.

3. Recognizing the success of the SU(3) symmetry and at the same time the difficulty of specifying the fundamental triplet, Ne'eman and Gell-Mann proposed the Eightfold Way.^{27),28)} They assumed that low-lying hadrons including baryons belong to the octet representation of SU(3) without identifying the fundamental triplet. Thus this is an algebraic theory, but not a model, and the fundamental ingredients of this theory are the 8 generators of SU(3) denoted by $F_i(i =$ 1,2,...,8) satisfying the commutation rela-



tions of the form

$$[F_i, F_j] = i f_{ijk} F_k, \qquad [4.2]$$

where f_{ijk} denotes the structure constant for the Lie algebra of SU(3). Furthermore, he introduced the densities or currents $\mathcal{F}_{i\alpha}(x)$ corresponding to the generators F_i by

$$F_i = \int \mathcal{F}_{i0}(x) d^3x, \qquad [4.3]$$

and tried to express various quantities in terms of densities.

Also, the phenomenological weak Fermi interactions are given in the form

$$\mathcal{H}_w = \frac{1}{\sqrt{2}} G_F J_\alpha^\dagger J_\alpha, \qquad [4.4]$$

and the current densities J_{α} and J_{α}^{\dagger} are assumed to satisfy commutation relations of the SU(2) algebra.

$$\begin{aligned} [J_0(\mathbf{x}, x_0), J_0^{\dagger}(\mathbf{x}', x_0)] \\ &= 2\delta^3(\mathbf{x} - \mathbf{x}')J_0^{(3)}(\mathbf{x}, x_0), \end{aligned}$$
[4.5]

$$\begin{aligned} [J_0(\mathbf{x}, x_0), J_0^{(3)}(\mathbf{x}', x_0)] \\ &= -2\delta^3(\mathbf{x} - \mathbf{x}')J_0(\mathbf{x}, x_0), \end{aligned}$$
[4.6]

$$\begin{aligned} [J_0^{\dagger}(\mathbf{x}, x_0), J_0^{(3)}(\mathbf{x}', x_0)] \\ &= 2\delta^3(\mathbf{x} - \mathbf{x}') J_0^{\dagger}(\mathbf{x}, x_0). \end{aligned}$$
[4.7]

Although the interaction [4.4] is phenomenological and still without neutral currents the above assumption that the current densities satisfy proper commutation relations is important in complying with the future adjustment of accommodating the gauge theory. An important contribution of the SU(3) theory is the prediction of the Ω^- mass. There is a decimet representation for excited baryons including the Δ resonances and one member called Ω^- had been missing. Gell-Mann²⁸ and Okubo²⁹ have derived a mass formula for the members of SU(3) multiplets in terms of I and Y by assuming a definite pattern of symmetrybreaking and predicted the mass of the missing Ω^- . Two examples of Ω^- of the predicted mass were observed at Brookhaven³⁰ and the SU(3) group received a strong support.

4. Then it was time for Gell-Mann³¹⁾ and Zweig³²⁾ to identify the triplet in SU(3) in order to proceed a step further. They invented a hypothetical triplet called quarks³¹⁾ or aces.³²⁾ The triplet quarks play a role similar to that of the Sakata triplet in mathematical sense, but they are considered to be unobservable when they are isolated. This property is referred to as quark confinement. Gell-Mann assumed that there are three kinds of quarks u, d and s which are represented by a common letter q. Low-lying baryons consist of three quarks qqq and low-lying mesons are bound states of a quark and an anti-quark $q\bar{q}$. This postulate reproduces the results of Eightfold Way.

Then the quark triplet inherits the isospin of the Sakata triplet so that we have

$$u \quad d \quad s$$

$$I_3 = \frac{1}{2}, \ -\frac{1}{2}, \ 0 \qquad [4.8]$$

and p, n and Λ are composed of quarks as

$$\mathbf{p} = (u, u, d), \ \mathbf{n} = (u, d, d), \ \Lambda = (u, d, s).$$
 [4.9]

The quarks carry fractional charges as is clear from [4.9]:

$$u \qquad d \qquad s Q = \frac{2}{3}e, \ -\frac{1}{3}e, \ -\frac{1}{3}e.$$
 [4.10]

Since a baryon consists of three quarks the baryon number of a quark is given by

$$B = \frac{1}{3}$$
. [4.11]

Then we are ready to introduce a new form of strangeness. In a quark model the quark number of a given flavor is conserved in strong and electromagnetic interactions.

$$N(u) = n(u) - n(\bar{u}),$$

$$N(d) = n(d) - n(\bar{d}),$$

$$N(s) = n(s) - n(\bar{s}).$$

[4.12]

In this quark model various quantum numbers can be expressed in terms of these quark numbers.

$$Q = e\left[\frac{2}{3}N(u) - \frac{1}{3}N(d) - \frac{1}{3}N(s)\right], \quad [4.13]$$

$$I_3 = \frac{1}{2} [N(u) - N(d)], \qquad [4.14]$$

$$B = \frac{1}{3} [N(u) + N(d) + N(s)].$$
 [4.15]

From these relations we can express strangeness S in terms of the strange quark number with reference to Eqs. [2.7] and [2.14] as

$$S = -N(s).$$

Thus in this quark model we find two alternative forms of strangeness. This model is unique in that it accepts both forms of strangeness. In the low energy phenomenology without quarks the second form -N(s) is not available, but in the next section we present a quark model which accepts only the second form of strangeness.

5. Algebra of weak currents and generations

So far we have discussed hadrons and leptons separately, but we find a close kinship between them in weak interactions. In 1959 Gamba, Marshak and Okubo³³⁾ recognized that weak interactions are symmetric under the exchange

$$p, n, \Lambda \leftrightarrows \nu, e, \mu.$$
 [5.1]

This means that the weak current J_{α} in [4.4] is symmetric under the exchange [5.1]. This operation is expressed in terms of the Sakata triplet, but it can easily be reexpressed in terms of the quark triplet as

$$u, d, s \leftrightarrows \nu, e, \mu.$$
 [5.2]

This symmetry is referred to as the Kiev symmetry or baryon-lepton symmetry. In 1962 the second neutrino ν_{μ} was discovered and the symmetry was modified to a new form by accommodating this new member as

$$u, d, c, s \leftrightarrows \nu_e, e, \nu_\mu, \mu,$$
 [5.3]

which implies introduction of a new quark called the charm quark.

Also, this symmetry makes it clear that the weak current J_{α} consists of two parts, the leptonic and the hadronic weak currents as

$$J_{\alpha} = J_{\alpha}^{(l)} + J_{\alpha}^{(h)}.$$
 [5.4]

Since J_0 , J_0^{\dagger} and $J_0^{(3)}$ satisfy commutation relations of the Lie algebra SU(2),³⁴ [4.5]–[4.7], also the leptonic and hadronic currents satisfy the same set of commutation relations, separately. Therefore, the algebra of leptonic weak currents is isomorphic to the algebra of hadronic weak currents. Furthermore, the baryon-lepton symmetry implies that there must be a one-to-one correspondence between irreducible representations of these two algebras. These requirements lead us to the concept of generations later.

In what follows we are going to construct these currents in terms of the leptonic and quark fields, and for this purpose we start from the leptonic current that is better known phenomenologically, namely,

$$J_{\alpha}^{(l)} = i\bar{\nu}_e\gamma_\alpha(1+\gamma_5)e + i\bar{\nu}_\mu\gamma_\alpha(1+\gamma_5)\mu, \quad [5.5]$$

corresponding to the electron and the muon families. Then, our problem is to find its hadronic counter expression, and the simplest solution is given by

$$J_{\alpha}^{(h)} = i\bar{u}\gamma_{\alpha}(1+\gamma_5)d, \qquad [5.6]$$

but this form is incomplete on some accounts and we are going to improve it in two directions.

1. It was suggested by Gell-Mann and Lévy³⁵⁾ and also by Cabibbo³⁶⁾ that we have to introduce s in order to describe the strangeness-changing transition, thereby respecting universality between β decay and μ decay, and d in [5.6] was replaced by d':

$$J_{\alpha}^{(h)} = i\bar{u}\gamma_{\alpha}(1+\gamma_5)d', \qquad [5.7]$$

$$d' = d \cdot \cos \theta + s \cdot \sin \theta, \qquad [5.8]$$

where θ is called the Cabibbo angle. The current in [5.7] still satisfies the required commutation relations.

2. Adopting the baryon-lepton symmetry under [5.3] we may add another term:

$$J_{\alpha}^{(h)} = i\bar{u}\gamma_{\alpha}(1+\gamma_5)d + i\bar{c}\gamma_{\alpha}(1+\gamma_5)s. \quad [5.9]$$

This expression is faithful to the symmetry under [5.3]. In Sec. 3 we have introduced the electron family and the muon family, and the baryon-lepton symmetry makes it possible to adopt the concept of family to counter sets of quarks. Thus the set (u,d) forms a family corresponding to the electron family, and (c,s)to that of the muon family. Then combining the electron family with the corresponding quark family (u,d), the first generation of fermions, consisting of (ν_e, e) and (u,d), is formed. By the same token the second generation of fermions consists of (ν_{μ}, μ) and (c, s).

Now we are going to merge these improvements with one another in constructing the representation of the hadronic current in terms of the quark fields. Eq. [5.9] does not allow strangeness-changing transitions so that we replace d and s by d' and s', respectively in [5.9], where

$$\binom{d'}{s'} = \binom{\cos\theta & \sin\theta}{-\sin\theta & \cos\theta} \binom{d}{s}.$$
 [5.10]

The new form of $J_{\alpha}^{(h)}$ is given by

$$J_{\alpha}^{(h)} = i\bar{u}\gamma_{\alpha}(1+\gamma_5)d' + i\bar{c}\gamma_{\alpha}(1+\gamma_5)s'.$$
 [5.11]

which does not change the commutation relations of SU(2). Glashow, Iliopoulos and Maiani³⁷⁾ obtained this form by requesting suppression of the strangeness-changing part in the neutral current in order to suppress the decay rate

$$K_L^0 \to \mu^+ + \mu^-.$$
 [5.12]

Indeed, in this case we have

$$[J_0^{(3)}, N(s)] = 0. [5.13]$$

Since we have introduced generation-mixing for the quarks without changing the commutation relations for currents we could introduce the same modification to leptons by replacing ν_e and ν_{μ} in [5.5] by ν'_e and ν'_{μ} , respectively

$$\begin{pmatrix} \nu'_e \\ \nu'_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta' & \sin\theta' \\ -\sin\theta' & \cos\theta' \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}. \quad [5.14]$$

The generation-mixing of neutrinos causes the socalled neutrino oscillation as predicted by Maki, Nakagawa and Sakata,³⁸⁾ and its experimental confirmation was made by the Super-Kamiokande group³⁹⁾ much later. No. 9]

Finally we shall discuss the impact of the discovery of the charm quark on the concept of strangeness. For a long time Λ and s had been considered to be charge singlets since there had been no isospin partners. In 1974 the charm quark cwas observed in the form of $J/\psi^{40,41}$ (in 1971 a pair of naked charm particles had been observed in cosmic rays⁴²⁾), but it was one order of magnitude more massive than s. Then it was natural that the presence of c had never been noticed in low energy phenomenology. Also, it was a good approximation at low energies to treat s as a charge singlet. Despite its tremendous success we then had to switch from SU(3) back to SU(2) by regarding c and s as members of a charge doublet, and now we have two sets of quarks (u, d) and (c, s) belonging to the doublet representation. Then we have

$$Q = \frac{2}{3}e, \qquad I_3 = \frac{1}{2} \quad \text{for } u \text{ and } c,$$
$$Q = -\frac{1}{3}e, \quad I_3 = -\frac{1}{2} \quad \text{for } d \text{ and } s, \quad [5.15]$$

and

$$B = \frac{1}{3}$$
 for all quarks. [5.16]

Thus we find

$$Y = B = \frac{1}{3} \quad \text{for all quarks}, \qquad [5.17]$$

and consequently it follows that strangeness S vanishes identically for all quarks including the strange quark!!

Fortunately, we have an alternative definition of strangeness [4.16], and we identify -N(s) with the strangeness in the quark models. Interpretation of properties of strangeness discussed in low energy phenomenology in Sec. 2 can be reproduced by this new definition. For instance, pair production of strange particles is realized by production of the quark pair s and \bar{s} , literally a pair production. Furthermore in low energy phenomenology s combines with u's and d's to form strange baryons, and \bar{s} combines with u or d to form K^+ or K^0 , and we have positive excess of the K mesons.

In weak interactions the selection rule $\Delta N(s) = 0$ is realized by the quark transitions

$$d \leftrightarrows u,$$
 [5.18]

by any of the hadronic weak currents [5.6], [5.7],

[5.9] and [5.11]. On the other hand, the selection rule $\Delta N(s) = \pm 1$ is obeyed by the transitions

$$s \leftrightarrows d,$$
 [5.19]

valid for the weak currents [5.7] and [5.11]. There are two s quarks involved in Ξ^0 and Ξ^- ,

$$\Xi^0 = (u, s, s), \ \Xi^- = (d, s, s).$$
 [5.20]

The weak interaction [4.4] induces $s \to d$, but only one *s* quark makes this transition in one step so that the transitions obeying $\Delta N(s) = \pm 2$ are forbidden and Ξ^- cannot decay directly into $n + \pi^-$.

All the properties of strangeness in the old version are described by [5.11] and are inherited by its new version. The new version is generic and all other quark numbers such as N(u), N(d) and N(c)share exactly the same set of rules with strangeness. For instance, all of them are conserved in strong and electromagnetic interactions.

We have shown that the interpretation of strangeness is model-dependent and have given two versions of it depending on the absence or presence of quarks. In this section we have put emphasis on the introduction of the concept of generations, and for that purpose we needed at least two generations. Once this concept is established, we can introduce the third generation as well. Indeed, Kobayashi and Maskawa introduced the third generation in order to accommodate CP violation in the gauge theory.⁴²⁾ The models described in this article are phenomenological but they would serve as the starting point in developing the gauge theory of electroweak interactions. Indeed, Eq. [2.7] served as the basis for the gauge theory.

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Profile

Kazuhiko Nishijima, a member of the Japan Academy, was born in 1926. He graduated from University of Tokyo in 1948 with a BS degree in physics and started his research career in 1950 at Osaka City University under Prof. Yoichiro Nambu. In 1953 he introduced the concept of strangeness in collaboration with Tadao Nakano. At that time he was interested in the question of how to derive the covariant S matrix elements for reactions involving composite particles starting from the time-ordered Green's functions. This work was accepted as a dissertation and he received a Doctor of Science degree in 1954 from Osaka University. In 1956 he visited Max-Planck-Institut fuer Physik in Goettingen and he succeeded in formulating reduction formula for composite particles. This is often called Haag-Nishijima-Zimmermann construc-



tion of composite particle fields. In 1957 he visited IAS in Princeton and completed the paper on HNZ construction. In 1957 he also proposed the two-neutrino theory from which two separate conservation laws follow, namely, conservation of the electron family and that of the muon family. From 1959 to 1966 he joined University of Illinois. During this period his main interests had been focused on time-ordered Green's function. One of the important results was a set of identities obtained by taking four-divergence of Green's function involving conserved current and other field operators. This set happens to be a generalization of the Ward-Takahashi identities connecting the vertex function with the electron propagator in QED. After returning to Japan he had been affiliated with University of Tokyo, Kyoto University and Chuo University, and has been interested mainly in color confinement based on asymptotic freedom. In 2003 he was awarded the Order of Culture by the Government of Japan.