Conception of Generations

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In this article of a brief acount is given of how the concept of generatinos has been formed in paritcle physics.

§1. Introduction

In particle physics many important discoveries have bee nmade of (1) new particles, (2)new processes or new interactions and finally (3) new concepts.

In this article we shall discuss formtaion of the concept of generations over a span of decades. Now we know that there are three generations of quarks and leptons and that each generation consists of two kinds of quarks and also two kinds of leptons.

The members of the second generation are more massive than the corresponding ones of the first generation ane by the same token those of the third generation are even more massive.

For this reason, members of the second and third generations decay quickly into those of the first generation.

Therefore, we are surronded by the members of the first generation alone in our daily life, and the short-lived members of the second and third generations cannot be recognized unless they are produced either by accelerators or by cosmic rays. Thus it is natural that the concept of generatinos has been shaped in parallel with the developement of accelerators.

In the following sections we shall review a brief history of how the concept of generatons has been formed.

§2. The First Generation

In the twenties at the dawn of quantum mechnics the only known fundamental interactions in atomic physics had been the electromagnetic ones and the only known particles had been the electron, the proton and the photon.

In the thirties with the entrance of nuclear physics on the stage it was realized that we were in need of new kinds of interactions and particles. If we assure that a number of photons must be equal to the atomic weight A and that of electrons must be equal to $A-Z$, where Z denotes the atomic number. Therefore, a nucleus of odd atomic number must obey Fermi statistics under the above assumption. This conclusion is contradicted, however, by nuclei such as ${}_3\mathrm{Li}^6$, ${}_7\mathrm{N}^{14}$, $\cdots$ which are known to obey Bose statistics experimentally. This strongly suggests the existence of unknown constituents of nuclei other than the proton and the electron.

Another difficulty at that time was the continuous energy spectrum of the electrons emitted in beta-decays suggesting the failure of the energy conservation law. In order to overcome this difficulty Pauli introduced his "neutrino" in 1930. He assumed that nuclei are composed of electrons, protons, and "neutrinos", and in order to confine "neutrinos" inside nuclei he also assumed that his "neutrino" has a magnetic moment through the so-called Pauli term and obeys the Dirac equation of the form

$$\left(\gamma_\mu \frac{\partial}{\partial x_\mu} + i\mu_{\mathrm{P}}\gamma_\mu\gamma_\nu F_{\mu\nu} + m\right)\psi = 0. \tag{2·1}$$

Then in 1932 Chadwick discovered the neutron that resolved all the troubles mentioned above qualitatively. In 1933 immediately after this discovery Heisenberg and Ivanenko independently proposed that nuclei are composed of protons and neutrons. This new nuclear model and Pauli's "neutrino" were merged by Fermi$^{1)}$ to account for the beta-decay in 1934. He introduced a field-theoretical interaction to induce the following spontaneous decay of the neutron:

$$\mathrm{n} \to \mathrm{p} + \mathrm{e}^- + \bar{\nu}. \tag{2·2}$$

Thus it is no longer necessary to confine the "neutrino" inside nuclei. In this way Fermi introduced the weak interaction into field theory for the first time.

The next question that was naturally raised was about how protons and neutrons or nucleus interact with each other in order to form nuclei. Known interactions cannot account for the nuclear forces in question as we shall see below.

(1) The gravitational interactions are too weak. For instance, the ratio of the gravitational forces to the electromagnetic ones between two protons is of the order of 10^{-36}.

(2) The Coulomb forces are absent between two neutrons and also between a neutron and a proton and repulsive between two protons.

(3) The exchange of an electron-neutrino pair between a proton and a neutron is too weak and the dependence of the nuclear forces resulting from such an exchange is proportional to r^{-5} in contradiction to experiment.

Thus in 1935 Yukawa introduced the meson theory$^{2)}$. He introduced the following interactions:

$$\mathrm{n} \to \mathrm{p} + \pi^-, \qquad \mathrm{p} \to \mathrm{n} + \pi^+. \tag{2·3}$$

Exchange of a pi-meson or a pion between a pair of proton and neutron results in the static potential

$$V(r) \propto \frac{1}{r}e^{-\mu r} \tag{2·4}$$

called the Yukawa potential. It is worth stressing that the force range is given by the Compton wave lengths of the meson μ^{-1}.

Yukawa introduced the strong interaction into field theory for the first time by assuming the existence of a new particle, a pi-meson or a pion.

From the experimental investigation of nuclear forces a novel feature of strong interactions has bee recognized. This is charge independence of nuclear forces. The nuclear forces between two protons, between two neutrons and between a neutron and a proton are approximately equal in the same angular momentum states,

$$V_{\rm pp} \simeq V_{\rm nn} \approx V_{\rm np} \quad \text{in} \quad {}^1\mathrm{S}, {}^3\mathrm{P}, {}^1\mathrm{D}, \cdots . \tag{2·5}$$

We now regard "proton" and "neutron" as two distinct charge states of a nucleon and these two states are distinguished by an operator I_3. A proton state is its eigenstate with the eigenvalue $\frac{1}{2}$ and a neutron state with the eigen value $-\frac{1}{2}$. Charge symmetry amounts to a symmetry under unitary transformations which mix the proton and neutron states, and this is the isospin group $SU(2)$. Mathematically this group is isomorphic to the group of space rotations.

Strong interactions are invariant under this group and its consequences in meson theory had been investigated by Kemmer$^{3)}$ in 1938 with the consequence that pions should exist in three charge states π^+, π^0, π^- corresponding to $I_3 = 1, 0, -1$. Isospin is the generator of the group $SU(2)$ and its three components satisfy the same set of commutation relations as that of angular momentum.

§3. Discovery of the Muon

From the experimentally known range of the nuclear forces Yukawa predicted the pion to be about 200 times as massive as the electron. Such a particle could not be produced by accelerators at that time because of the limitation of energy, and experimentalists tried to detect the pions in cosmic rays.

In 1937 two American groups and one Japanese group succeeded to observe cosmic ray particles of the predicted mass. They were Neddermeyer and Anderson$^{4)}$, Street and Stevenson$^{5)}$, and Nishina, Takeuti and Ichinomiya$^{6)}$.

The cosmic ray meson, now called the muon, had the right mass, but it was not clear whether it was identical with the pion predicted by Yukawa. The key-point was to check their nuclear interactions, since they sometimes underwent Rutherford scattering. To this effect Tomonaga and Araki$^{7)}$ in 1940 studied the role played by Coulomb interactions between a meson and a nucleus in nuclear absorption, and their conclusions may be summarized as follows:

(1) When a slow negative pion approaches a nucleus it is attracted by the nucleus and is subsequently absorbed.

(2) On the other hand a slow positive pion is repelled by the nucleus and decays without being absorbed.

In 1945 Conversi, Piccioni and Pancini$^{8)}$ experimentally studied the nuclear interactions of cosmic ray mesons or muons and observed that the negative mesons were absorbed by iron ($Z = 26$) but decayed without being absorbed by carbon($Z = 6$) in contradiction to the prediction of Tomonaga and Araki.

This problem was further analyzed carefully in 1947 by Fermi, Teller and Weisskopf$^{9)}$ with the conclusion that there is a discrepancy of factor 10^{12} if the cosmic ray mesons were identified with the Yukawa meson.

All these observations tend to suggest that the cosmic ray meson μ is not identical with the Yukawa meson π.

The Bristol group$^{10)}$ observed the decay of a pion into a muon which successively decayed into an electron,

$$\begin{array}{l} \pi^+ \longrightarrow \mu^+ + \cdots \\ \qquad\quad \hookrightarrow e^+ + \cdots \end{array}$$

in nuclear emulsion in 1946. Cosmic rays produce pions by strong interactions with the atmosphere, then pions decay into muons which in turn decay into electrons by weak interactions.

Quite independently, Sakata, Inoue, Tanikawa and Nakamura[12), proposed the two-meson theory in 1946, and also Marshak and Bethe[13)made a similar proposal in 1947. Then what is the *raison d'être* of the muon?

Soon it became clear that the muon is a big brother of the electron, namely, the muons behave exactly the same way as the electrons except for the mass. This led us to a confusion, but by looking back we realize that the muon happened to be the first observed member of the second generation.

§4. Strange Particles

The pions were first observed in cosmic rays, but soon in 1948 artificial production of pions started in Berkeley. For a systematic investigation of pions accelerators are more useful than cosmic rays and in 1952 experimental study of pion-nucleon scattering took place in Chicago and the Δ resonances were discovered. Artificial pions played a vital role in establishing charge independence or the conservation of isospin in pion-nucleon interactions.

About the same time there was an important discovery in cosmic rays. In 1947 Rochester and Butler[14) observed two decay events in a cloud chamber experiment on the ground level. One of them was identified as a decay of a neutral particle and the other as that of a charged one. It was just the time when pions started to be identified and the time was not yet ripe to identify them. They were first called V particles from the shape of the fork tracks and later called strange particles. V particles preferred to be observed at high altitude and they really started to be observed abundantly at the mountain level.

Soon it became clear that they are produced abundantly by strong interactions but decay with relatively long lifetime by weak interactions. It had been a puzzle why they do not decay through strong interactions and for this reason they were named strange particles. Later many species of strange particle were found although we do not list them up here. In order to account for the reason why they do not decay through strong interactions the pair production hypothesis was proposed. Assume a parity-like quantum number denoted by P_V satisfying $P_V^2 = 1$. P_V is conserved in strong interactions but violated in weak interactions just as the space parity, and then we assign the following eigenvalues to particles(hadrons):

$$P_V = 1 \qquad \text{for pions and nucleons,} \tag{4·1}$$

$$P_V = -1 \qquad \text{for } V \text{ particles.} \tag{4·2}$$

Then V particles are produced in pairs by strong interactions but decay into known particles by weak interactions. Pair production was confirmed by the cosmotron experiment[15)]in 1953, namely,

$$\begin{aligned}\pi^- + \mathrm{p} &\to \Lambda^0 + \mathrm{K}^0,\\ &\to \Sigma^- + \mathrm{K}^+,\\ &\to \mathrm{n} + \pi^0.\end{aligned} \tag{4·3}$$

The quantum number P_V alone, however, could not account for the following properties:

(1) At low energies much more K^+ mesons are produced than K^- clearly exhibiting positive excess of K mesons.

(2) The meta-stability of the cascade particle Ξ^- against the following two modes of decay

$$\Xi^- \to \underset{(-)}{\Lambda^0} + \underset{(+)}{\pi^-}, \qquad \Xi^- \to \underset{(+)}{n} + \underset{(+)}{\pi^-} \tag{4·4}$$

cannot be explained with the P_V parity selection rule alone. We have given the eigen values of P_V under individual particles in (4·4). No matter whether $P_V = 1$ or -1 for Ξ^- it is not possible to forbid both decay modes by strong interactions. A possible solution is to promote the multiplicative quantum number P_V to an additive quantum number S called strangeness. For this purpose we shall recall the isospin and compare the eigenvalues of I_3 with the charges of isospin multiplets.

Table I. Isopin Multiplets

particles	π^+	π^0	π^-	p	n	Δ^{++}	Δ^+	Δ^0	Δ^-
I_3	1	0	-1	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{3}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{3}{2}$

It is clear from this table that we have

$$\Delta Q = \mathrm{e}\Delta I_3. \tag{4·5}$$

This means that an increase of I_3 by 1 in a given charge multiplet results in the corresponding increase of the charge by the unit charge e. By integrating this difference equation we find

$$Q = \mathrm{e}\left(I_3 + \frac{Y}{2}\right), \tag{4·6}$$

where Y denotes the constant of integration characteristic of a given charge multiplet and is called hypercharge. Then we find

$$Y = B \qquad \text{for the first generation,} \tag{4·7}$$

$$Y = B + S \qquad \text{for } V \text{ particles,} \tag{4·8}$$

where the totality of pions, nucleons and their composite particles form the first generation and S is called the strangeness. Apparently $S = 0$ for the first generation and P_V and S are related to one another through

$$P_V = (-1)^S, \tag{4·9}$$

BothP_V and S are not conserved in weak interactions but obey the selection rule

$$\Delta S = 0, \pm 1 \tag{4·10}$$

Strangeness was introduced in 1953[16,17]. The concept of hypercharge is very universal and it has been exploited also in gauge theories with some generalizations.

(1) In the original quark model the strange quark was considered to be an isospin singlet, but now it has been promoted to a member of an isospin doublet with the charm quark c as its partner.

(2) The concept of isospin and hypercharge has been extended to include leptons by adopting the same group structure $SU(2) \times U(1)$ as for quarks. $SU(2)$ is generated by I_1, I_2 and I_3 and $U(1)$ by Y.

§5. Models of Hadrons

In sixties hundreds of new particles were discovered by Bevatron and bubble chambers, and it became inconceivable that all of them represent elementary particles. Thus some authors tried to build models in which most particles are composed of a small number of really fundamental particles such as

(1) baryons p and n by Fermi and Yang[18],
(2) baryons p, n and Λ by Sakata[19],
(3) quarks u,d and s by Gell-Mann[20] and also by Zweig[21].

§6. Two Neutrinos

The relationship between the electron and the muon is mysterious. The latter is a big brother of the former, but the following processes seem to be forbidden:

$$\mu \nrightarrow e\gamma, \qquad \mu^- + \mathrm{p} \nrightarrow \mathrm{p} + \mathrm{e}^-. \tag{6·1}$$

This means that the muon is by no means an excited state of the electron, and in order to understand the selection rule Konopinski and Mahmoud[22] introduced the conservation of the lepton number in 1953. They have identified e^-, μ^+ and ν as leptons and e^+, μ^- and $\bar{\nu}$ as anti leptons and defined their lepton number by

$$L_{KM} = \mathrm{n}(\mathrm{e}^-, \mu^+, \nu_\mathrm{L}, \nu_R) - \mathrm{n}(\mathrm{e}^+, \mu^-, \bar{\nu}_L, \bar{\nu}_R). \tag{6·2}$$

where n stands for the number and the subscripts L and R denote the handedness of the neutrinos. Then it is clear that the processes in (6·1) are forbidden. Later Lee and Yang[23] gave an alternative identification of leptons. They identified e^-, μ^- and left-handed (anti) neutrinos as leptons and e^+, μ^+ and right-handed (anti) neutrinos as anti leptons, so that we have

$$L_{LY} = \mathrm{n}(\mathrm{e}^-, \mu^-, \nu_L, \bar{\nu}_L) - \mathrm{n}(\mathrm{e}^+, \mu^+, \nu_R, \bar{\nu}_R). \tag{6·3}$$

It so happens that both conservation laws are consistent with experiments so that the present author[23a)]has assumed in 1957 that both lepton numbers are conserved and by adding or subtracting (6·2) and (6·3) the following conserved quantities were obtained:

$$L_{\mathrm{e}} = \mathrm{n}(\mathrm{e}^-, \nu_L) - \mathrm{n}(\mathrm{e}^+, \bar{\nu}_R), \tag{6·4}$$

$$L_\mu = \mathrm{n}(\mu^-, \bar{\nu}_L) - \mathrm{n}(\mu^+, \nu_R), \tag{6·5}$$

Then by changing the notations as

$$\nu_L \to \nu_{\mathrm{e}}, \qquad \bar{\nu}_R \to \bar{\nu}_{\mathrm{e}} \tag{6·6}$$

$$\bar{\nu}_L \to \nu_\mu, \qquad \nu_R \to \bar{\nu}_\mu, \tag{6·7}$$

We find that there are two separate conservation laws of the electron number and of the muon number.

Anyway this is a clear indication of the existence of two lepton families or generations. The reason why this idea was not immediately extended to hadrons was that no corresponding conserved particle numbers were known for hadrons. Later it became known by the observation of neutrino oscillations that lepton numbers defined above are no longer conserved exactly either, but once the concept of generations is established conservation laws are not required to justify it. Also, it was difficult to extend the family concept to hadrons since it was before the introduction of the quark model.

The existence of two lepton families was confirmed in 1962 at AGS in Brookhaven by the Columbia group[24)].

§7. Baryon-Lepton Symmetry

In 1959 at the Kiev Conference Gamba, Marshak and Okubo[25)] reported that weak interactions are symmetric under the following replacement between leptons and baryons:

$$\nu,\ \mathrm{e},\ \mu \rightleftarrows \mathrm{p},\ \mathrm{n},\ \Lambda \tag{7·1}$$

In order to account for this symmetry the Nagoya group[26)] assumed that the fundamental baryons (p, n, Λ) are bound states of the leptons (ν, e, μ) and a boson B, respectively,

$$(\nu,\ \mathrm{e},\ \mu) + B^+ \to (\mathrm{p},\ \mathrm{n},\ \Lambda). \tag{7·2}$$

The idea that a neutrino is bound to a B reminds us of Pauli's "neutrino", but it has the merit of giving a correspondence between the family structure of leptons and that of baryons. What corresponds to the transition from Pauli's "neutrino" to Fermi's in this respect would be to interpret(7·2) as a fundamental interaction with B being most likely one of gauge bosons in GUT.

After the discovery of two neutrinos the symmetry under was extended to the one under (7.1) the following replacement[27)]:

$$\nu_{\mathrm{e}},\ \nu_\mu,\ \mathrm{e},\ \mu \rightleftarrows \mathrm{p},\ \mathrm{p}',\ \mathrm{n},\ \Lambda \tag{7·3}$$

This symmetry makes it possible to infuse the family structure of leptons into baryons, without the help of conservation laws, as

$$\begin{pmatrix}\nu_{\rm e}\\ {\rm e}^-\end{pmatrix} \rightleftarrows \begin{pmatrix}{\rm p}\\ {\rm n}\end{pmatrix}, \qquad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix} \rightleftarrows \begin{pmatrix}{\rm p}'\\ \Lambda\end{pmatrix}. \tag{7·4}$$

It is important to recognize that this correspondence implies the existence of the fourth fundamental particle. The quark model version of this correspondence will be discussed in the next section.

§8. Flavor Mixing and Generations

Let us denote the coupling constant for the $\mu - {\rm e}$ decay

$$\mu^+ \to e^+ + \nu_{\rm e} + \bar{\nu}_\mu \tag{8·1}$$

as G_F and that for the beta-decay (2·2) as G_β. In the quark model G_β is also the coupling constant for the beta-decay of the d quark into the u quark,

$${\rm d} \to {\rm u} + {\rm e}^- + \bar{\nu}_{\rm e}. \tag{8·2}$$

Experimentally, G_β is slightly smaller than G_F. If we should insist on the strict universality of the Fermi interactions there must be a reason for this deviation. Apart from the detailed coupling type, the Fermi interaction for the beta-decay(8·2) is given by

$$G_\beta\ (\bar{u}\ d)(\bar{e}\ \nu_{\rm e}) + {\rm h.c.}, \tag{8·3}$$

and Cabibbo[28)] assumed that its complete form should be given by

$$G_F\ (\bar{u}\ d')(\bar{e}\ \nu_{\rm e}) + {\rm h.c.}, \tag{8·4}$$

where

$$\begin{pmatrix}d'\\ s'\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}d\\ s\end{pmatrix}. \tag{8·5}$$

The parameter θ denotes the Cabibbo angle and if we identify the strangeness conserving part of (8·4) with (8·3) we find

$$G_\beta = G_F \cos\theta < G_F. \tag{8·6}$$

On the other hand the strangeness-changing part of (8·4)is given by

$$G_F \sin\theta(\bar{u}\ s)(\bar{e}\ \nu_e) + {\rm h.c.} \tag{8·7}$$

and it reproduces the experimental beta-decay rates of strange baryons fairly well. The Cabibbo interaction (8·4) is also consistent with the selection rule (4·10).

The branching ratio of the decay process

$${\rm K}_L^0 \to \mu^+ + \mu^- \tag{8·8}$$

is smaller than 7×10^{-9} and this process must be suppressed much more than the prediction of the Cabibbo theory. In order to remedy this defect Glashow, Iliopoulos and Maiani modified (8·4) by adding a new term involving a new quark c as

$$G_F[(\bar{u}\ d^{'}) + (\bar{c}\ s^{'})]\ (\bar{e}\ \nu_{\mathrm{e}}) + \mathrm{h.c.}. \tag{8·9}$$

This means that the quark s originally treated as an isoopin singlet is promoted to a member of an isospin doublet with the new quark c as its partner.

In the Cabibbo theory the neutral current generated from the charged ones $(\bar{u}\ d^{'})$ and $(\bar{d}^{'}\ u)$ is proportional to

$$(\bar{u}u) - (\bar{d}^{'} d^{'}) \tag{8·10}$$

which has a strangeness-changing component giving rise to too large a branching ratio for (8·8). The corresponding neutral current in the GIM theory, however, is proportional to

$$(\bar{u}u) + (\bar{c}c) - (\bar{d}^{'} d^{'}) - (\bar{s}^{'} s^{'}) = (\bar{u}u) + (\bar{c}c) - (\bar{d}d) - (\bar{s}s), \tag{8·11}$$

so that there is no change of strangeness or flavor in the limit of exact $SU(2)$ symmetry implying the suppression of the process (8·8).

It is interesting to observe that the introduction of the fourth quark c corresponds to that of $\mathrm{p}^{'}$ in the Nagoya model$^{27)}$, and the quark model version of (7·4) turns out to be given by

$$\begin{pmatrix} \nu_{\mathrm{e}} \\ \mathrm{e} \end{pmatrix} \rightleftarrows \begin{pmatrix} \mathrm{u} \\ \mathrm{d} \end{pmatrix}, \qquad \begin{pmatrix} \nu_{\mu} \\ \mu \end{pmatrix} \rightleftarrows \begin{pmatrix} \mathrm{c} \\ \mathrm{s} \end{pmatrix}. \tag{8·12}$$

When the two lepton families and the corresponding two quark families are merged, respectively, two generations emerge.

$$\begin{aligned} \text{first generation}: &\quad \nu_{\mathrm{e}}, \mathrm{e}, \mathrm{u}, \mathrm{d} \\ \text{second generation}: &\quad \nu_{\mu}, \mu, \mathrm{c}, \mathrm{s} \end{aligned} \tag{8·13}$$

Now we are in a position to summarize the fate of the muon. When it was discovered it was treated as an uninvited guest since its *raison d'être* could not be understood, but now it has been recognized that the muon is the oldest or the most senior member of the second generation. This fate of the muon reminds us of a fairy tale of Andersen called “Ugly Duckling.” A baby swan was left with a duck family, but he was called an ugly duckling since he was different and was bullied by other baby ducks. Later when he was grown up he recognized his real identity and knew where he belongs to, and he joined a swan family to live happily thereafter.

In 1964 violation of CP invariance was observed in the decay process $\mathrm{K}_L^0 \rightarrow 2\pi$ $^{29)}$. Later in 1973 Kobayashi and Maskawa$^{30)}$ recognized that three generations of quarks and leptons are needed in order to incorporate CP violation into the gauge theory of electroweak interactions and generalized the flavor-mixing matrix (8·5) to a three-dimensional one called the Kobayashi-Maskawa matrix. The KM matrix depends on three Euler angles and one CP violating phase. In this way the third generation was predicted theoretically.

In 1974 the long-awaited quark c was observed in the combination $c\bar{c}$ called J/ψ 31),32) and existence of the second generation was established.

It is worth emphasizing that quarks and leptons cooperate hand in hand to prevent anomalies from emerging by maintaining the grouping of elementary particles in the form of generations33).

In this article we have tried to clarify how the concept of generations was born by the efforts of many physicists both theorists and experimentalists over a period of decades.

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