# Emergence of the Second Generation in Particle Physics

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## 1. Elementary Particles

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|---|---|
| Subatomic Particles | Elementary Particles<br>Composite Particles |

How to define elementary particles ?

Fundamental fields in the Lagrangian represent elementary particles.

Experimental distinction between elementary and composite particles is very difficult.
Heisenberg (1957)

We quote two examples in which the definition of elementary particles given above does not work.

### 1) Axiomatic Field Theory

In this approach field theory is studied based on general principles such as Lorentz invariance and causality without specifying the Lagrangian.
H.Lehmann, K.Symanzik and W.Zimmermann

In this case it is possible to construct a local field for a particle composed of other particles.
R.Haag(1958), K.Nishijima(1958) and W.Zimmermann(1958)

2) Nuclear Democracy or Bootstrap

An S matrix theory based on dispersion relations and unitarity.
Denial of the existence of the Lagrangian
Berkeley group(sixties)

In general a model is defined by specifying a set of elementary particles.

## 2. Weak and Strong Interactions

The dynamical properties of atoms and also of molecules are governed mainly by the electromagnetic interactions.

The entry of nuclei implies introduction of new kinds of interactions.

### 1) Weak Interactions

field theory of beta-decay in terms of the so-called Fermi interaction, first attempt to give shape to weak interactions.

$$n \rightleftarrows p + e^- + \bar{\nu}$$

Earliest paper to enlist the neutrino as an elementary particle accepting suggestion of Pauli.
E.Fermi(1934)

2) Strong Interactions

field theory of nuclear forces in terms of the Yukawa coupling

$$p \rightleftarrows n + \pi^+, \quad n \rightleftarrows p + \pi^-$$

where $\pi$ denotes the Yukawa meson.
H.Yukawa(1935)

The range of the nuclear forces
= the Compton wave length of the meson

Derivation of this relation by Wick based on the uncertainty principle.
G.C.Wick(1938)

3) Meson Decay

Yukawa also introduced the meson decay interactions.

$$\pi^- \rightleftarrows e^- + \bar{\nu}, \quad \pi^+ \rightleftarrows e^+ + \nu$$

Then the beta-decay proceeds in two steps.

$$n \to p + \pi^- \to p + e^- + \bar{\nu}$$

It is similar to the gauge theory of beta-decay:

$$n \to p + W^- \to p + e^- + \bar{\nu}$$

At present we know that neither Fermi's decay interaction nor Yukawa's one is fundamental, but they are closely related to one another through a dispersion relation which can be applied without specifying the fundamental decay interaction. This is the celebrated Goldberger-Treiman relation.

M.L.Goldberger and S.B.Treiman(1958)

$$2Mg_A = \sqrt{2}\, G f_\pi$$

$M$ : nucleon mass
$G$ : pion-nucleon coupling
$f_\pi$ : pion decay constant
$g_A$ : axial-vector coupling constant in the Fermi interaction

## 3. Discovery of the Muon

Yukawa's prediction that the meson Compton length is given by the range of the nuclear forces led to

$$m_\pi \approx 200\, m_e$$

Search for the cosmic ray particles of the predicted mass had been carried out in USA and Japan.

S.Neddermeyer and C.D.Anderson (1937)
T.C.Street and E.C.Stevenson (1937)
Y.Nishina , M.Takeuti and T.Ichimiya(1937)

Later studies in late forties led to the right mass of $200m_e$ and a lifetime of $2\times10^{-6}$ sec for the cosmic ray mesons.

## 1) Fate of Positive and Negative Mesons stopped in Matter

Tomonaga and Araki concluded that , in practice, all positive mesons at rest in matter should undergo spontaneous decay; whereas all negative mesons should disappear through nuclear capture by the effect of the nuclear Coulomb field.
S.Tomonaga and G.Araki (1940)

The above conclusion had been drawn for Yukawa's mesons, but a question was raised as to whether cosmic ray mesons be identical with the former since the nuclear interactions of the latter appeared to be weaker than had been expected.

## 2) The Rome Experiment

Conversi, Pancini and Piccioni, then at University of Rome conducted an decisive

experiment which demonstrated that negative cosmic ray mesons stopped in Carbon decayed at variance with the prediction of Tomonaga and Araki although they were absorbed in Lead.
Then the absorption process was carefully analyzed by Fermi, Teller and Weisskopf with the conclusion that the nuclear interactions of the cosmic ray mesons are weaker than those of the Yukawa mesons by 12 orders of magnitude.
From now on the cosmic ray meson and the Yukawa meson will be referred to as the muon and pion, respectively. This is called the two-meson theory.
M.Conversi, M.Pancini and O.Piccioni (1947)
N.Fermi, E.Teller and V.Weisskopf (1947)

### 3) Two-Meson Theory

In order to understand the difference in the strength of nuclear interactions between the Yukawa meson and the cosmic ray meson Tanikawa assumed as early as in 1942 that they are not identical but that there must be two kinds of mesons. His unpublished idea was further advanced by Sakata and Inoue, however, and these works were published first in Japanese and later after the end of the WWII in English.

S.Sakata and T.Inoue (1942, 1946)
T.Tanikawa (1946)

In 1947 Marshak and Bethe also proposed a two-meson hypothesis at the Shelter Island Conference.
R.E.Marshak and H.A.Bethe (1947)

Experimentally Powell's group of Bristol University had already observed the decay of a pion into a muon and neutral particles in the nuclear emulsion directly. This observation confirmed the existence of two kinds of mesons , but this result had not been known to other groups because of poor communication at that time.
C.F.Powell et al (1947)

Gradually it became clear that the muon and the electron share almost exactly the same properties except for the difference in mass and has nothing to do with Yukawa's meson. Then, the muon was an uninvited guest since nobody at that time understood why it exists. Indeed, Isidor Rabi once exclaimed: "Who ordered the muon?"

## 4) Universal Fermi Interaction

The entry of the muon set the stage for a variety of Fermi interactions.

Pontecorvo compared

$$\mu^- + p \to n + \nu,$$

$$e^- + p \to n + \nu$$

and concluded that the Fermi coupling constants for these processes are of the same order of magnitude.

Klein compared

$$\mu^\pm \to e^\pm + \nu + \bar{\nu},$$

$$n \to p + e^- + \bar{\nu}$$

and reached the same conclusion as Pontecorvo's.

The equality of these interactions suggests that they are mediated by intermediate field with respect to which all particles have the same charge.

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|---|---|
| B.Pontecorvo | (1947) |
| O.Klein | (1948) |
| P.Tiomno and J.A.Wheeler | (1949) |
| Q.Puppi | (1949) |
| R.D.Lee, M.Rosenbluth and C.N.Yang | (1949) |

## 4. Charge Independence for Hadrons

Discovery of the neutron in 1932 by Chadwick led Heisenberg, Iwanenko and others to propose that nuclei are composed of protons and neutrons.

## 1) Introduction of Isospin

Soon in 1936 observation of the binding energies and energy levels of mirror nuclei enabled us to conclude that pp- and nn- interactions are equal except for the Coulomb corrections.
This symmetry is called charge symmetry.

Then the pp- and pn- interactions were studied experimentally and from the analysis of the results the pp- and pn- interactions in singlet S states are found to be equal within experimental error. This symmetry is referred to as charge independence of nuclear forces and this property is expressed in terms of conserved isospin.

The concept of charge independence (CI) applies originally to hadrons, namely, particles with strong interactions. Isospin was first defined for the proton and neutron.

$$I_3 | p \rangle = \frac{1}{2} | p \rangle, \quad I_3 | n \rangle = -\frac{1}{2} | n \rangle$$

It was stressed by Pauli that pions responsible for the nuclear forces should be formulated so as to be consistent with CI, so Kemmer introduced neutral pion so that we can assign isospin to pions.

$$I_3|\pi^+\rangle = |\pi^+\rangle,\ I_3|\pi^0\rangle = 0,\ I_3|\pi^-\rangle = -|\pi^-\rangle$$

$I_3$ increases by 1 when the charge increases by e and the sum of $I_3$ over a given multiplet is 0. The above statement can be expressed by

$$\Delta Q = e\Delta I_3$$

The three components of isospin satisfy the same commutation relations as those of the angular momentum so that the symmetry group is SU(2).
The solution of the above difference equation is given by

$$Q = e\left(I_3 + \frac{Y}{2}\right)$$

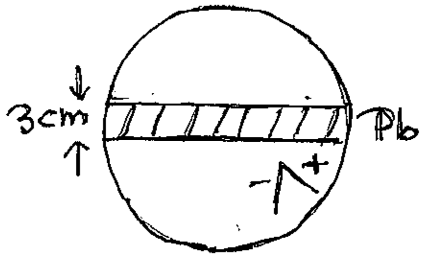
where Y is a quantum number assigned to each charge multiplet and is called hypercharge. Y=0 for the pion multiplet and Y=1 for the nucleon multiplet, so that until early fifties it had been believed that Y=B, where B denotes the baryon number.

## 2) V Particles in Cosmic Rays

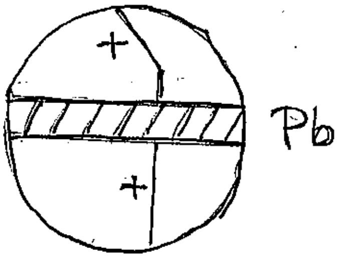
Rochester and Butler of Manchester University observed two V events using a cloud chamber with a single lead plate inside.

$V^0$ : 15 Oct. 1946
$V^+$ : 23 May 1947

After that observation was continued in vain.



$V^0$



$V^+$

Soon it was recognized that one has to go up to high altitude in order to observe V particles in time before they decay.

Cal Tech (Anderson's group) 1949
$6V^0$ Pasadena
$24V^0$, $4V^+$ White Mountain
Manchester July 1950~ March 1951
$51V^0$, $12V^+$ Pic du Midi

From their abundance it was clear that they are produced by strong interactions, but from their rather long lifetimes of the order of $10^{-10}$ sec it was also clear that they decay through weak interactions. Why they do not decay through strong interactions, that was a serious question about V particles, and for this reason they started to be called strange particles.

In order to account for this mismatch let us assume, as many authors at that time did, that there is a new multiplicative quantum number which we tentatively call V parity denoted by $P_V$ We assume that it is conserved in strong interactions but not in weak interactions just as the space parity. We assign positive V parity to conventional hadrons or strongly interacting particles such as nucleons and pions and negative V parity to V particles. Then it is clear that V particles are produced in pairs and decay only through weak interactions.

This hypothesis could not be confirmed by cosmic ray experiments since it is not easy to observe both decays of a pair of V particles in a single picture. For this reason experimentalists gradually moved from cosmic rays to accelerators.

## 3) From Cosmic Rays to Accelerators

In 1953 Cosmotron (3GeV) at Brookhaven started to produce V particles and succeeded in confirming the pair production hypothesis.

In this experiment the following processes have been observed:

$$\pi^- + p \rightarrow \Sigma^- + K^+,$$

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

In these events decay products of both V or strange particles have been identified. From this experiment it became possible to assign isospin to strange particles.

We give some of the isospin assignments below.

| | | | |
|---|---|---|---|
| $\Lambda^0$ | I=0, | Y=0, | B=1 |
| $\Sigma^+, \Sigma^0, \Sigma^-$ | I=1, | Y=0, | B=1 |
| $K^+, K^0$ | I=1/2, | Y=1, | B=0 |

In July 1953 a Conference on Cosmic Rays was held at Bagnère de Bigorre. In this Conference C.F.Powell addressed to the participants:
“Gentlemen, we have been invaded.....
The acceralerators are here....”

W.B.Fowler, R.P.Shutt, A.M.Thorndike , W.L. Whittemore(1953) Cosmotron experiment

## 4) Introduction of Strangeness

As is clear from the assignments of various quantum numbers given above the hypercharge Y is not always equal to the baryon number B and this equality has been modified as

$$Y = B + S$$

where S is called strangeness. It is equal to 0 for the conventionally known particles around us, but it is non-zero for the strange particles.

S= −1 for $\Lambda^0, \Sigma$

S= 1 for $K^+, K^0$

S is conserved in strong interactions but not in weak interactions and obeys the selection rule

$$\Delta S = 0, \pm 1$$

and it is related to the V parity through

$$P_V = (-1)^S$$

In strong interactions we have two kinds of conservation laws, namely, of isospin and hypercharge corresponding to the symmetry group SU(2) × U(1). This symmetry was taken over by the gauge theory of electroweak interactions.
M.Gell-Mann (1953)
T.Nakano and K.Nishijima (1953)

## 5. Models of Hadrons

### 1) Fermi-Yang and Sakata Models

After the experimental discovery of artificial pions Fermi and Yang pushed forward a hypothesis that pions may be composite particles formed by the association of a nucleon with an antinucleon. They hoped to prevent the number of elementary particles from increasing indefinitely. After the discovery of strange particles Sakata added the $\Lambda$ particle to nucleons as the fundamental constituents of hadrons. Then, on the basis of the assumption that p, n and $\Lambda$ are equal partners in this model, Ikeda, Ogawa and Ohnuki and also independently Yamaguchi introduced the SU(3) symmetry into the Sakata model.

This model was successful for clarifying the octet structure of the pseudoscalar mesons involving pions, but it failed in reproducing the mutiplet structure of baryons since the triplet representation had been assigned wrongly to p, n and $\Lambda$. Remedy of this defect led us to the Eightfold Way proposed by Gell-Mann.

| | |
|---|---|
| E.Fermi and C.N.Yang | (1949) |
| S.Sakata | (1956) |
| M.Ikeda, S.Ogawa and Y.Ohnuki | (1959) |
| Y.Yamaguchi | (1959) |

### 2) Eightfold Way.

Contrary to the prediction of Sakata model it seemed to be the best to assign the octet representation to baryons. In 1961 Gell-Mann proposed the Eightfold Way by maintaining the approximate symmetry SU(3) and assigning the octet representation to low-lying hadrons such as baryons, pseudoscalar mesons and vector mesons without specifying the fundamental triplet. So this is not a model but a symmetry argument. Similar proposals were made for the octet vector mesons by Ne'eman and by Salam and Ward.

For an assumed pattern of SU(3) breaking Gell-Mann and also Okubo successfully derived a celebrated mass formula for hadrons and contributed to establishment of the Eightfold Way.

| | |
|---|---|
| M.Gell-Mann | (1961) |
| Y.Ne'eman | (1961) |
| A.Salam and J.C.Ward | (1961) |
| S.Okubo | (1962) |

### 3) Quark Model

The question of the fundamental triplet in the SU(3) symmetry was finally resolved by introduction of fractionally charged fermions called quarks u, d and s with charge 2/3,-1/3 and -1/3, respectively, but it took some time for this model to be accepted. Gradually the consensus converged to its acceptance. At that time we had SU(3) but not yet the idea of generations.
M.Gell-Mann (1964)

## 6. Two Neutrinos

So far we have discussed properties of hadrons but we shall come back to leptons, namely, fermions which do not interact strongly.

### 1) Lepton Conservation

In order to account for the absence of certain weak processes Konopinski and Mahmoud tried to introduce a conservation law for the lepton number similar to the baryon number. Later, however, Lee and Yang modified it by giving an alternative definition of the lepton number.
K-M assumed that $e^-$ , $\mu^+$ and $\nu$ are leptons and $e^+$ , $\mu^-$ and $\bar{\nu}$ are antileptons, whereas L-Y assumed that $e^-$ , $\mu^-$ and left-handed $\nu$ and $\bar{\nu}$ are leptons and $e^+$ , $\mu^+$ and right-handed $\nu$ and $\bar{\nu}$ are antileptons. In either case the conserved lepton number is defined as the number of leptons minus that of antileptons. It seemed that both versions of the conservation laws are consistent with experiments. So what will happen if we assume that both are right?
E.J.Konopinski and H.M.Mahmoud (1953)
F.D.Lee and C.N.Yang (1957)

### 2) Two Neutrinos

In 1957 the author has assumed that the lepton numbers in two alternative versions are both conserved. They are given, respectively, by

$$L_{KM} = N(e^-, \mu^+, \nu_L, \nu_R) - N(e^+, \mu^-, \bar{\nu}_L, \bar{\nu}_R),$$

$$L_{LY} = N(e^-, \mu^-, \nu_L, \bar{\nu}_L) - N(e^+, \mu^+, \nu_R, \bar{\nu}_R)$$

Let us take their sum and difference in order to clarify their physical significance. They are given by

$$L_e = N(e^-, \nu_L) - N(e^+, \bar{\nu}_R), \quad (\nu_L \equiv \nu_e, \ \bar{\nu}_R \equiv \bar{\nu}_e)$$

$$L_\mu = N(\mu^-, \bar{\nu}_L) - N(\mu^+, \nu_R), \quad (\bar{\nu}_L \equiv \nu_\mu, \ \nu_R \equiv \bar{\nu}_\mu)$$

We started from a four-component neutrino and it is split into two two-component neutrinos, one associated with the electron and the other with the muon. Thus we have two families of leptons, the electron family and the muon family, conserved separately. The same idea was also proposed by Schwinger.
K.Nishijima (1957)
L.Schwinger (1957)

In 1962 the two neutrino hypothesis was confirmed experimentally by the Columbia group using AGS at Brookhaven. They have shown that the neutrino beam arising from the pion-muon decay generates only muons but not electrons when the neutrinos hit nuclei as predicted from the lepton conservation laws.
G.T.Danby et al(1962)

Later observation of the neutrino oscillation has shown that these conservation laws are approximate, but they served to form the concept of lepton families or generations. It took a much longer time to extend this idea to quarks for various complications to be mentioned below.

## 7. Baryon-Lepton Symmetry

After the discovery of parity violation in weak interactions the structure of the Fermi interactions turned out to be the next favorite subject of study. In 1958 the V-A theory of Fermi interactions was proposed and the universality of the Fermi coupling constant was recognized for various Fermi interactions.

Gamba, Marshak and Okubo have asserted that weak interactions, or to be more precise, the weak V-A current $J_\alpha$ is symmetric under the interchange

$$\nu, e, \mu \rightleftarrows p, n, \Lambda$$

It is interesting to observe that p, n and $\Lambda$ form the fundamental triplet in the Sakata model whereas $\nu$, e and $\mu$ were used as a fictitious triplet in Gell-Mann's Eightfold Way.

A.Gamba, R.E.Marshak and S.Okubo (1959)

In 1962 the existence of two neutrinos was confirmed experimentally and the above correspondence can be generalized to

$$\nu_e, \nu_\mu, e, \mu \rightleftarrows p, p', n, \Lambda$$

Existence of a baryon p' is implied by the baryon-lepton correspondence. Then a natural question was immediately raised: "Which representation of SU(3) p' would belong to ? " Because of the success of SU(3) we had been spellbound to SU(3) at that time.

In any case we could expect that the baryon-lepton symmetry would help us translate the family structure of leptons into that of quarks provided that we could find a proper group and proper representations for leptons and quarks. As we shall see soon we had to go back to SU(2) again from SU(3) despite its tremendous phenomenological successes.

## 8. Strangeness-Changing Fermi Interactions

### 1) Universal Fermi Interactions

The standard form of the universal Fermi interaction may be expressed by

$$\frac{G}{\sqrt{2}} J_\alpha^\dagger J_\alpha$$

where $J_\alpha$ is the sum of the leptonic and hadronic currents.

$$J_\alpha = J_\alpha^{(l)} + J_\alpha^{(h)}$$

Phenomenologically they are given by

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

$$J_\alpha^{(h)} \approx \lambda \bar{p} \gamma_\alpha (1 + \alpha \gamma_5) n$$

We identify G with the coupling constant $G_\mu$ for

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Then $G_\mu$ is slightly larger than $G_\beta$ for

$$n \to p + e^- + \bar{\nu}_e$$

Gell-Mann and Lévy attributed this discrepancy to the replacement of n by n',

$$n' = \frac{1}{\sqrt{1+\varepsilon^2}} (n + \varepsilon \Lambda)$$

with

$$G_\beta = \frac{1}{\sqrt{1+\varepsilon^2}} G_\mu$$

so as to introduce strangeness-changing amplitude.

M.Gell-Mann and M.Lévy (1960)

In accordance with SU(3) symmetry we can express currents in terms of 8 generators $F_i$ of SU(3) and their vector densities $\mathcal{F}_{i\alpha}$ and axial-vector densities $\mathcal{F}_{i\alpha}^5$.

electric current density

$$j_\alpha = e\left(\mathcal{F}_{3\alpha} + \frac{1}{\sqrt{3}} \mathcal{F}_{8\alpha}\right)$$

weak current density

$$J_\alpha^{(h)} = \left[\mathcal{F}_{1\alpha} + \mathcal{F}_{1\alpha}^5 + i\left(\mathcal{F}_{2\alpha} + \mathcal{F}_{2\alpha}^5\right)\right] \cos\theta + \left[\mathcal{F}_{4\alpha} + \mathcal{F}_{4\alpha}^5 + i\left(\mathcal{F}_{5\alpha} + \mathcal{F}_{5\alpha}^5\right)\right] \sin\theta$$

Leptonic current is the same as before.
In the quark model we can replace p, n and $\Lambda$ in $J_\alpha^{(h)}$ by u, d and s, so that we may write as

$$J_\alpha^{(h)} = i\bar{u}\gamma_\alpha(1+\gamma_5)(d\cdot\cos\theta + s\cdot\sin\theta)$$

2) Cabibbo's Theory

In 1963 Cabibbo reproduced the beta-decay rates of hadrons group-theoretically by using this current, and the angle $\theta$ is called the Cabibbo angle.
N.Cabibbo (1963)

Now we come back to the baryon-lepton symmetry or better the quark-lepton symmetry. After the discovery of the second neutrino the proper correspondence should be given by

$$\nu_e, e, \nu_\mu, \mu \rightleftarrows u, d, c, s$$

where c is a new quark corresponding to $\nu_\mu$ which replaces p' introduced before.

3) GIM Mechanism

Glashow, Iliopoulos and Maiani modified $J_\alpha^{(h)}$ by adding a term involving c,

$$J_\alpha^{(h)} = i\bar{u}\gamma_\alpha(1+\gamma_5)(d\cdot\cos\theta + s\cdot\sin\theta)$$
$$+ i\bar{c}\gamma_\alpha(1+\gamma_5)(-d\cdot\sin\theta + s\cdot\cos\theta)$$

They have tried to explain the experimentally observed suppression of a strangeness-changing decay process

$$K_L^0 \to \mu^+ + \mu^-$$

by exploiting the new quark c.

Formally, we may conclude that only with this modification $J_0$ , $J_0^\dagger$ and $I_3$ can form an algebra su(2) provided that c and s form an isospin doublet just as u and d . In this way we were obliged to come back to SU(2) from SU(3). For a long time s had been considered to be an isospin singlet just as $\Lambda$ , but now it has been recognized that it has an isospin partner c.

Likewise, inclusion of leptons in $J_\alpha$ necessarily assign isospin to leptons and consequently also hypercharge to them, and this led us to the gauge theory of electroweak interactions based on the gauge group SU(2) ×U(1).

Then, the two-family structure of leptons is carried over to quarks by the quark-lepton symmetry:

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\rightleftarrows\begin{pmatrix}u\\ d\end{pmatrix}\qquad\qquad\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}\rightleftarrows\begin{pmatrix}c\\ s\end{pmatrix}$$

first generation second generation

In this way the concept of generations emerged

and paved the way to the gauge theory of electroweak interactions. Conceptually there is no essential difficulty to extend the idea of generations to the third generation.
S.L.Glashow, J.Iliopoulos and L.Maiani (1970)

## Appendix Ugly Duckling

In this talk I have tried to explain how the concept of generations emerged and how we have reached two generations or two families of basic
fermions.
First, we had known only the members of the first generation since those of the second generation decay quickly into those of the first one. Therefore, when members of the second generation such as muons and strange particles were discovered they were treated as uninvited guests and we were puzzled as illustrated by Rabi's exclamation: "Who ordered the muon?"

There is a close parallel between this history and a fairy tale by Christian Andersen, namely, "Ugly Duckling"
First, there was only one family on the scene, namely, the Duck family. Therefore, when a baby swan was left with them he was not welcome and was pecked by other baby ducks.
Later, however, when he was grown up he recognized his true identification and realized that he belongs to an honorable Swan family.

So we may name the quarks of the first and second generations keeping this story in mind.

# Naming of the Quarks

## Gell-Mann

| | | |
|---|---|---|
| first generation | (u)p | (d)own |
| second generation | (c )harm | (s)trange |

## Andersen

| | | |
|---|---|---|
| first generation | (u)gly | (d)uckling |
| second generation | (c )harming | (s)wan |

UGLY DUCKLING

CHARMING SWAN