Progress of Theoretical Physics, Vol. 64, No. 5, November 1980

Algebra of Subquark Charges

Hidezumi TERAZAWA

Institute for Nuclear Study, University of Tokyo
Tanashi, Tokyo 188

(Received June 11, 1980)

The algebra of subquark charges is discussed in a subquark model in which leptons and quarks are made of an isospin-doublet spinor subquark “wakem” and a color-quartet scalar subquark “chrom”. The unitarity of the quark (or lepton) mixing matrix for the weak charged currents is shown to hold due to the SU(2) algebra of subquark isospin charges. It is also shown that the mixing matrix element decreases as fast as or faster than the inverse of quark (or lepton) mass difference. If isospin-color changing supersymmetric charges of subquark are included, the algebra is not closed. The energy-momentum operator can, however, be expressed as the supersymmetric charge squared as usual if there are twice as many chroms as wakems, which is the case. Possible symmetry-breaking and quantum number dependence of the lepton and quark mass spectra are conjectured.

§ 1.

Recently many subquark models in which leptons and quarks are further made of more fundamental particles, the subquarks, have been proposed and discussed. However, some fundamental questions remain to be answered in these subquark models. They include 1) how to explain the lepton and quark mass spectra, 2) how to explain the quark (or lepton) mixings for the weak charged currents, 3) how to explain the fact that lepton (or quark) magnetic moments are so close to the Dirac ones in spite of the possible structure of leptons (or quarks), 4) how to explain non-existence (or no discovery) of leptons or quarks of spin 3/2 (or higher) and 5) how to explain non-existence (or no discovery) of exotic states of three subquarks or a subquark-antisubquark pair. All of these questions may not be answered precisely until the true theory of subquark dynamics, a possibly final theory in physics, becomes available. Some of them, however, may be answered without knowing the detail of subquark dynamics.

In this paper, such an attempt to answer some of these questions without specifying subquark dynamics is reported. To this end, the algebra of subquark charges is discussed in a simple subquark model in which leptons $f^{\text{w}}$ and quarks $f^{\text{chn}}$ ($i=1, 2, 3$) are made of an isospin-doublet spinor subquark “wakem” $w_{\alpha} (\alpha = 1, 2)$ and a color-quartet scalar subquark “chrom” $C_{\alpha} (\alpha = 0, 1, 2, 3)$ as

$$f^{\text{w}} = (w_{\alpha} C_{\alpha})_{\alpha} = \begin{cases} \nu_{\alpha} & \text{for } \alpha = 1, \alpha = 0 \\ l_{\alpha} & \text{for } \alpha = 2, \alpha = 0 \\ u_{\alpha} & \text{for } \alpha = 1, \alpha = i \\ d_{\alpha} & \text{for } \alpha = 2, \alpha = i. \end{cases} \quad (1)$$
A difference between leptons and quarks in different generations (the quantum numbers \( n = 1, 2, 3, \ldots, N \)) is regarded as dynamical. As a result, the unitarity of the quark (or lepton) mixing matrix for the weak charged currents is shown to hold due to the \( SU(2) \) algebra of subquark isospin charges. It is also shown that the mixing matrix element decreases as fast as or faster than the inverse of quark (or lepton) mass difference. If isospin-color changing supersymmetric charges of subquark are included, the algebra is not closed. The energy-momentum operator (and, therefore, the lepton and quark masses) can, however, be expressed as the supersymmetric charge squared as usual if there are twice as many chroms (or colors) as wakems (or isospin states), which is the case. Finally, possible symmetry-breakings and quantum number dependence of the lepton and quark mass spectra are conjectured.

\section{2.}

Consider the free Lagrangian for subquarks \( \omega_a \) and \( C_a \) with an equal mass \( M \)

\begin{equation}
L = \bar{\omega}_a (i \gamma \partial - M) \omega_a + \bar{C}_a \gamma^\alpha C_a - M C_a^\dagger C_a^*.
\end{equation}

This Lagrangian generates the following 36 conserved currents including Miyazawa's supersymmetric currents:

\begin{align}
\psi_\mu &= \bar{\omega}_a \gamma_\mu \omega_a, \quad b_\mu = \frac{1}{3} i C_i \gamma^\beta \delta_\mu C_i, \quad \lambda_\mu = i C_i \gamma^\beta \delta_\mu C_i,
\end{align}

\begin{align}
\nu_\mu &= \bar{\omega}_a \gamma_\mu \frac{1}{2} (\tau_i)_{ab} \omega_b, \quad \lambda_\mu^A = i C_i \gamma^\beta \frac{1}{2} (\lambda^A)_i C_j,
\end{align}

\begin{align}
x_\mu &= i C_i \gamma^\beta \delta_\mu C_i, \quad x_\mu^a = i C_i \gamma^\beta \delta_\mu C_a,
\end{align}

\begin{align}
s_\mu &= M \bar{\psi}_a C_a - i \bar{\psi}_a \gamma_\mu \omega_a, \quad \bar{s}_\mu = M \bar{\omega}_a \gamma_\mu C_a^* + i \bar{\omega}_a \gamma_\mu \omega_a^*,
\end{align}

where \( \delta_\mu = \gamma_\mu - \frac{1}{2} \gamma_5 \), and \( \tau_i \) and \( \lambda^A \) are the Pauli matrices of \( SU(2) \) and the Gell-Mann matrices of \( SU(3) \), respectively. The corresponding conserved charges are

\begin{align}
W &= \int d^3x \bar{\omega}_a \gamma_\mu \omega_a, \quad B = \frac{1}{3} i \int d^3x C_i \gamma^\beta \delta_\mu C_i, \quad L = i \int d^3x C_i \gamma^\beta \delta_\mu C_i,
\end{align}

\begin{align}
I_i &= \int d^3x \bar{\omega}_a \gamma_\mu \frac{1}{2} (\tau_i)_{ab} \omega_b, \quad M^i = i \int d^3x C_i \gamma^\beta \frac{1}{2} (\lambda^A)_i C_j,
\end{align}

\begin{align}
X_i &= i \int d^3x C_i \gamma^\beta \delta_\mu C_i, \quad X_i^a = i \int d^3x C_i \gamma^\beta \delta_\mu C_a,
\end{align}

\begin{align}
S^{aa} &= \int d^3x (M \bar{\psi}_a C_a - i \bar{\psi}_a \gamma_\mu \omega_a^*), \quad \bar{S}^{aa} = \int d^3x (M \bar{\omega}_a \gamma_\mu C_a^* + i \bar{\omega}_a \gamma_\mu \omega_a^*).
\end{align}
The first 20 currents or charges form an algebra of $U(2) \times U(4)$,

$$[I_i, I_j] = i\epsilon_{ijk} I_k, \quad [A^A, A^B] = i f_{ABC} A^C,$$

$$[X_i, X_j] = -\delta_{ij} (B - L) + (\lambda^A)_{ij} A^A,$$

$$[B, X_i] = -\frac{1}{3} X_i, \quad [L, X_i] = -X_i,$$

$$[A^A, X_i] = -\frac{1}{2} (\lambda^A)_{ij} X_j, \quad [A^A, X^i] = X_i \frac{1}{2} (\lambda^A)_{ii},$$  \hspace{0.5cm} (5)

where $f_{ABC}$ are the structure constants of $SU(3)$ and all the other commutators vanish.

The first commutation relation which makes the $SU(2)$ algebra of weak isospins $I_i$ yields the familiar relation

$$[I_i, I_j] = 2I_i,$$  \hspace{0.5cm} (6)

where $I_i = I_i^+ + i I_i^-$. This relation immediately indicates the unitarity of the quark (or lepton) mixing matrix $U$ for the weak charged currents. More precisely, in the subquark model the weak charged currents of leptons and quarks are taken as matrix elements of the more fundamental subquark currents between quarks (or leptons) which are not eigenstates of the weak isospin, e.g.,

$$\langle u_m | \bar{u}_n \gamma_\mu (1 - \gamma_5) u_i | d_n \rangle = U_{mn} U_{mi} (1 - \gamma_5) d_n,$$  \hspace{0.5cm} (7)

where the indices $m$ and $n$ denote the generation numbers ($m, n = 1, 2, 3, \ldots, N$).

The quark (or lepton) mixing matrix $U_{mn}$ is more simply defined by

$$\langle u_n | I_i | d_m \rangle = U_{mn}.$$

Then, the relation (6) sandwiched between $\langle d_n |$ and $| d_n \rangle$ ($\langle u_n |$ and $| u_n \rangle$) leads to the unitarity of $U_{mn}$, $UU^\dagger = U^\dagger U = 1$, if the intermediate states $u_i(d_i)$ form a complete set for states with quantum numbers of an up (down) quark, i.e.,

$$|u_i\rangle \langle u_i| = 1, \quad |d_i\rangle \langle d_i| = 1$$  \hspace{0.5cm} (9)

This demonstration of the unitarity of the quark (or lepton) mixing matrix is similar to the recent one by Višnjić-Triantafillou, but more general. If a similar consideration is applied to the current commutation relation instead of the charge commutation relation and if continuum intermediate states are taken into account, the "Adler relation" for quark structure functions can be derived as discussed in Ref. 1).

Suppose that the subquark dynamics is described by the Hamiltonian which consists of an isospin symmetric part and an isospin breaking perturbation part $H_L$. Then, the mixing matrix elements are approximately calculated to be
\[ U_{mn} = \frac{\langle u_m^a | H_I | u_n^b \rangle}{m_{u_m} - m_{u_n}} + \frac{\langle d_m^a | H_I | d_n^b \rangle}{m_{d_m} - m_{d_n}} \quad \text{for } m \neq n, \]  

where \( u_m^a \) and \( d_n^a \) denote the unperturbed quark states. This indicates that the mixing matrix element between different generations decreases as fast as or faster than the inverse of mass difference between the relevant quarks (or leptons) unless the symmetry breaking force enhances a particular transition matrix element between different unperturbed states. This property of the quark (or lepton) mixing matrix seems to be very natural and can be taken as a successful consequence of the subquark model.

In order to investigate the full symmetry possessed by subquarks, it is necessary to include the supersymmetric currents or charges in the algebra. It is, however, difficult to make a closed algebra when the supersymmetric currents or charges are included, which will be seen in what follows. The commutation relations of the ordinary charges and the supersymmetric charges are simply given by

\[
\begin{align*}
[W, S^{sa}] &= -S^{sa}, & [W, \bar{S}^{sa}] &= S^{sa}, \\
[B, S^{st}] &= -\frac{1}{3} S^{st}, & [B, \bar{S}^{st}] &= \frac{1}{3} S^{st}, \\
[L, S^{ra}] &= -S^{ra}, & [L, S^{ra}] &= S^{ra}, \\
[I, S^{ra}] &= -\frac{1}{2} \left\langle \tau_i \right\rangle_{a}^{b} S^{ra}, & [I, \bar{S}^{ra}] &= S^{ra} \frac{1}{2} \left\langle \tau_i \right\rangle_{a}^{b}, \\
[A', S^{st}] &= -\frac{1}{2} \left\langle \lambda^f \right\rangle_{l}^{f} S^{st}, & [A', \bar{S}^{st}] &= S^{st} \frac{1}{2} \left\langle \lambda^f \right\rangle_{l}, \\
[X_i, S^{ra}] &= -\delta_{i}\bar{S}^{ra}, & [X_i, \bar{S}^{ra}] &= S^{ra}, \\
[X_i, \bar{S}^{ra}] &= -\delta_{ia} S^{ra}, & [X_i, S^{ra}] &= \bar{S}^{ra}.
\end{align*}
\]

The anticommutation relations between the supersymmetric charges are somewhat complicated as

\[
\{S^{sa}, S^{sb}\} = M \left( \frac{1}{2} \gamma^\mu \partial_{\mu} W^{sa} - \delta_{a}^{b} C^{sa} \right) + \gamma^\mu \left( \frac{1}{2} \gamma_{c}^{b} P_{\mu}^{bs} + \delta_{a}^{b} P_{\mu}^{sa} \right) - \frac{1}{2} \gamma^{\mu} \gamma^{n} \delta_{a}^{b} Y_{\mu}^{sa} - \frac{1}{2} \gamma^{a} \gamma^{b} \delta_{a}^{b} \gamma_{\mu}^{n}
\]

(12)

and

\[
\{S^{sa}, \bar{S}^{sb}\} = \{\bar{S}^{sa}, S^{sb}\} = 0,
\]

where

\[
W^{sa} = \int d^3x (\psi_s \bar{\psi}_a), \quad C^{sa} = i \int d^3x \bar{C}_\beta \gamma^\mu \partial_\mu C_a,
\]
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\[ P^a_{\mu} = \int d^3 x \left[ (\psi^\dagger \gamma^\mu \gamma^\nu \psi) - g_{\mu} \tilde{\psi} \gamma^\nu (i \gamma^\mu - M) \psi \right], \]

\[ P^{as}_{\mu} = \int d^3 x \left[ \partial_{\mu} C^a_{\beta} \partial^a C^a_{\alpha} + \delta^a C^a_{\beta} \partial \partial \partial \partial C^a_{\alpha} - g_{\mu} \tilde{\psi} \gamma^\nu \psi \right], \]

\[ Y^{as}_{\mu} = \int d^3 x \left[ (\psi^\dagger \gamma^\mu \gamma^\nu \psi) - g_{\mu} \tilde{\psi} \gamma^\nu (i \gamma^\mu - M) \psi \right] + M g_{\mu}^i (\psi^\dagger \gamma^i \psi), \]

\[ Z^{as}_{\mu} = \int d^3 x \left[ g_{\mu}^i g_{\mu}^i \gamma^\nu \gamma^\nu \psi \right] - g_{\mu} \tilde{\psi} \gamma^\mu (i \gamma^\nu - M) \psi. \]

Since the right-hand side of the relation (12) contains not only the energy-momentum-like operators with internal quantum numbers \( P^a_{\mu} \) and \( P^{as}_{\mu} \) but also the "pseudo-energy-momentum" \( Y^{as}_{\mu} \) and the spin-dependent term \( Z^{as}_{\mu} \), there is no way to obtain a closed graded algebra with the conserved charges. However, it is clear from the relation (12) that the energy-momentum given by

\[ P_\mu = P^a_{\mu} + P^{as}_{\mu} \]  

(14)

can be written in terms of the supersymmetric charges as

\[ P_\mu = \frac{1}{8} \text{Tr} (\gamma_\mu (S^{as}, \bar{S}^{as})) \]  

(15)

as in ordinary supersymmetry theories. Notice that \( \delta_{aa} = 4 \) and \( \delta_{aa} = 2 \) have been used in obtaining the above relation. Therefore, the energy-momentum can be expressed as the supersymmetric charge squared as usual only if the number of chroms (or colors) is twice as large as the number of wakems (or isospin states). This mysterious luck is closely related to the point that both the spinor isodoublet \( \psi_\alpha \) and the scalar color-quartet \( \psi_\alpha \) have an equal number of physical states. In any case, the lepton and quark mass can be taken as eigenvalues of the supersymmetric charge squared as

\[ \frac{1}{8} \text{Tr} (S^{as}, S^{as}) = m_{\psi_{\alpha}} | f^{as}_{\alpha} \rangle \]  

(16)

for \( P = 0 \).

Also, the subquark mass can be written in terms of the supersymmetric charges as

\[ M = \frac{1}{8} \text{Tr} (S^{as}, S^{as}) / (W - C) \]

with

\[ C = C^{as} = 3B + L. \]  

(17)

Furthermore, all the ordinary charges, \( I_\alpha, A^i, X_\alpha \) and \( X^i_\alpha \), can also be expressed,
as the supersymmetric charge squared as

\[
I_i = \frac{1}{16M} \text{Tr} [(\tau_i)_{S} \{S_{\text{se}}, S_{\text{be}}\}],
\]

\[
A^a = -\frac{1}{16M} \text{Tr} [(\lambda^a)_{\mu} \{S_{\text{se}}, S_{\text{ae}}\}],
\]

\[
X_i = -\frac{1}{18M} \text{Tr} (S^{st}, S^{se}) \quad \text{and} \quad X'_i = -\frac{1}{18M} \text{Tr} (S^{se}, S^{at}),
\]

which are all derived from the relation (12).

§ 3.

Let us now consider the symmetry-breaking which leads to the physical spectra of lepton and quark masses. To do that, just imagine where lepton and quark masses come from. The subquarks in this model have either an isospin or a color-spin but not both. Therefore, known interactions between the subquarks, \(w\) and \(C\), inside a lepton or quark are restricted to electromagnetic interaction (and possibly gravitational one, but no isospin-isospin or color-spin-color-spin interactions) between the charges, \(Q_w\) and \(Q_C\) (the masses, \(M_w\) and \(M_C\)) possessed by the subquarks in a classical picture. Since the Coulomb energy is proportional to \(Q_w Q_C\), a symmetry breaking due to the electromagnetic interaction may behave as the total charge squared \(Q^2\) of a lepton and quark, leaving the terms proportional to \(Q_w^2\) and \(Q_C^2\) to be absorbed into the subquark self-masses. Another obvious origin of the symmetry breaking is a possible mass difference of subquarks. This symmetry breaking may generate terms which depend on \(I_i\) or \(B-L\) since

\[
M_w = \frac{1}{2} (M_{w_1} + M_{w_2}) + (M_{w_1} - M_{w_2}) I_8
\]

and

\[
M_C = \frac{1}{4} (3M_{C_1} + M_{C_2}) + \frac{3}{4} (M_{C_1} - M_{C_2}) (B-L).
\]

Actually, however, if the Gell-Mann-Nishijima sum rule \(Q = I_8 + (B-L)/2\) is satisfied, \(I_8\) is not independent of \(Q\) and \(B-L\). Therefore, the lepton and quark masses may be determined by \(Q\) and \(B-L\), and possibly by unknown dynamical quantum numbers, if any.

Now take a look at the gross structure of the lepton and quark mass spectra

\[
\begin{pmatrix}
  m_{e} & m_{\mu} & m_{\tau} & \cdots \\
  m_{e} & m_{\mu} & m_{\tau} & \cdots \\
  m_{u} & m_{c} & m_{t} & \cdots \\
  m_{d} & m_{s} & m_{b} & \cdots
\end{pmatrix}
\rightarrow
\begin{pmatrix}
  0 & 0 & 0 & \cdots \\
  0 & 1 & 17 & \cdots \\
  0-3 & 10-15 & ? & \cdots \\
  0-3 & 1-5 & 45-50 & \cdots
\end{pmatrix},
\]
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where quark masses are very ambiguous, depending on whether they are current or constituent quark masses. However, one can find that one of the best candidates for the mass formula for leptons and quarks is given by

\[
m_{\text{sub}} = m_{\nu} \left| B-L \right|^{n} = \begin{cases} 
0 & \text{for } \nu \smallint \\
\frac{Q^2}{4} & \text{for } l \smallint \\
12m_{\nu}n^4 & \text{for } u \smallint \\
3m_{\nu}n^4 & \text{for } d \smallint 
\end{cases}
\]

(21)

The possibility of some singular dependence of the mass on \( B-L \) has recently been suggested by Marshak and Mohapatra. However, such singular dependence may not be essential in the above empirical mass formula since \( (B-L)^{-1} \) can always be replaced by \( (\frac{1}{2} + B-L) \) for a lepton or quark. Also, the \( n^4 \)-dependence of the charged lepton mass spectrum has been proposed by Barut in his particular dynamical model of leptons. Although this empirical mass formula would fail for the fourth charged lepton (the predicted mass \( \sim 9 \text{ GeV} \)), if any, it must be taken more seriously for \( n=0,1,2 \) if a topponium (a bound state of \( t\bar{t} \)) is found to have the mass around 40 GeV.

In any case, our aim is not to find a better empirical mass formula but to find a possible subquark dynamics which leads to such a mass formula as (21) for leptons and quarks. Let us consider possible origins of lepton and quark masses one by one. 1) Subquark masses: In the zeroth approximation, the mass of a lepton or quark is a sum of the masses of constituent subquarks, \( M_{\nu} + M_{\nu} \). As mentioned previously, the sum depends on the quantum numbers \( I \) and \( B-L \). However, such a dependence is linear on \( I \) or \( B-L \) to the lowest order of the breaking but never quadratic or higher as in (21). 2) Interaction energies: Also, as mentioned previously, the electromagnetic (mutual or self-) interaction energy of a compound state of subquarks can easily depend on \( Q^2 \). It is also conceivable that the energy depends on \( (B-L)^2 \) if there exists an interaction of subquarks coupling with the charge of \( B-L \). Then, how can these quantum numbers \( Q \) and \( B-L \) closely couple with each other in the energy as in (21)? In addition to possible but unfavorable higher order effects of the above interactions, there are some other possibilities: The factor of \( B-L \) or \( I \) comes from the subquark mass while the remaining factor such as \( Q^2 \) does from the interaction. Remember, as an example, that the binding energy of a hydrogen atom is proportional to \( m_{\text{H}}\alpha^2 \). The gravitational interaction is another possibility since, in a classical picture, it is proportional to \( M_{\nu} \cdot M_{\nu} \) which may depend on \( I \cdot (B-L) \). It becomes relevant for a candidate for subquark dynamics if the subquark masses are as large as the Planck mass or if the size of a lepton or quark is as small as the Planck length. 3) Spontaneous generation: As emphasized by Marshak and Mohapatra, this possibility is favorable for producing a singular dependence of the mass on quantum numbers. For example, a self-consistency equation of \( m = mR^2 \ln (A/m^2) \) yields a
symmetry-breaking result of $m = A \exp(-1/2R^2)$ where $R$ is some quantum number and $A$ is a certain mass scale or cutoff.

§ 4.

More difficult to imagine is what is happening in the horizontal direction of leptons and quarks. What is the meaning of the generation quantum number $n$ such as the one in the mass formula (21)? Suppose that an approximate horizontal symmetry such as $SU(N)$ exists with the breaking proportional to a certain member of the horizontal spin. Then, the factor such as $n'$ can be taken as an eigenvalue of the horizontal spin. If, however, the existing generations of leptons and quarks are caused by subquark dynamics as assumed in this paper, the generation quantum number $n$ is purely dynamical. In this case, the dependence of lepton and quark masses on $n$ is the best clue to subquark dynamics. Although the $n'$ dependence as in (21) should not be taken too seriously, it seems meaningful that the leptons and quarks in the first generation can be taken as essentially massless particles. Then, it is natural to ask why they are. In view of the possible isospin-color changing supersymmetry discussed in this paper, it is very tempting to consider these leptons and quarks in the first generation as Nambu-Goldstone fermions corresponding to the supersymmetric charges $S^{aA}$, which appear when the global supersymmetry is broken spontaneously. The problem of how to cope with the low-energy theorems of Nambu-Adler type remains to be solved, though.

All the above considerations are highly speculative and not at all concrete. No particular dynamical model of subquarks has been proposed. It seems certain that one will be in a better position to specify subquark dynamics when more leptons and more quarks are found and more precise information on their mass spectra and mixings is given. However, in conclusion, we would like to propose a completely new dynamical model of subquarks which seems to be promising. It is the “subcolor” $SU(3)$ Yang-Mills gauge theory for subquark dynamics. The point is that the subquark binding force may be due to some new charges (or quantum numbers) of subquarks which are different from any one of the charges discussed in this paper. Suppose that there exist spinor subquarks which have an arbitrary number of internal symmetry indices (including flavors and the ordinary colors) in general and which are subcolor triplet (the subcolor indices $i=1,2,3$). Then, the “subchromodynamics” for subquarks is simply described by the Lagrangian

$$L = \bar{s}i\gamma Ds - \frac{1}{4} (G^A_{\mu})^2,$$

with

$$D_s = \partial_s - ig \frac{1}{2} \lambda^A G_s^A$$ and $$G^A_{\mu} = \partial_s G_s^A - \partial_s G_s^A + gf^{ABC} G_s^B G_s^C,$$ (22)
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where $g$ is a coupling constant and $G_s^a$ are "subgluon" fields. This subchromodynamics certainly promises, as the usual chromodynamics, the possible confinement of subquarks inside not only leptons and quark which are subcolor singlet states of three subquarks ($\sim \epsilon_{ijk} s_i s_j s_k$) but also the ordinary gauge bosons (and Higgs scalars) which are also subcolor singlet states of a subquark-antisubquark pair ($\sim s_i s_i^\dagger$). This repetition of chromodynamics at the subquark level should be taken seriously and is a subject for future investigation.

Acknowledgement

The author would like to thank Dr. K. Akama and the colleagues in his Theory Division of Institute for Nuclear Study for useful discussions.

References

1) See, for example, H. Terazawa, Phys. Rev. D22 (1980), 184, and references therein.
10) See, for example, S. Weinberg, in Festschrift in honor of I. I. Rabi (N. Y. Acad. of Science, 1977).
   For recent study, see F. Wilczek and A. Zee, Phys. Rev. Letters 42 (1979), 421.