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# REMARKS ON THE UNIFIED MODEL OF ELEMENTARY PARTICLES

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*(presented by Z. Maki)*

## I. INTRODUCTION

According to the unified model suggested by Sakata *et al.*,[1] the fundamental baryons $p$, $n$ and $\Lambda$ were supposed to be compound systems of leptons and a new sort of matter $B^+$:

$$p = \langle \nu B^+ \rangle, \quad n = \langle e^- B^+ \rangle, \quad \Lambda = \langle \mu^- B^+ \rangle .$$

Some important symmetry properties of particles such as the baryon-lepton (BL-) symmetry [2] and the full symmetry (or unitary symmetry) [3] of strong interactions may be well interpreted by this scheme (the Nagoya model). But, in so far as we confine our discussion to these points, we could not find a clue to push forward our scheme to cover more involved properties of elementary particle interactions. In this report, we shall therefore concentrate our attention on some embarrassing problems which would destroy compactness of the unified scheme of elementary particles.

One of these problems is the possible existence of two kinds of neutrinos,[4] one associated with electron and the other with muon. We shall begin our discussion with this point.

## II. TWO NEUTRINO THEORY AND A MODIFIED BARYON-LEPTON SYMMETRY

Let us introduce *the weak neutrinos* $\nu_e$ and $\nu_\mu$ through a leptonic weak current:

$$j_\lambda = (\bar{e}\nu_e)_\lambda + (\bar{\mu}\nu_\mu)_\lambda , \qquad (1)$$

where $(\bar{e}\nu_e)_\lambda = (\bar{e}\gamma_\lambda(1+\gamma_5)\nu_e)$ etc. They are stable massless fermions unless other interactions are introduced.

In order to find a way to link this scheme with the BL-symmetry principle, it should be noticed that the neutrinos from which a corresponding baryon (say $p$) should be constructed are not necessarily the weak neutrinos themselves; there may be a possibility that the *true neutrinos* are different from $\nu_e$, $\nu_\mu$, but defined by their linear combination:

$$\left.\begin{aligned} \nu_1 &= \nu_e \cos\delta + \nu_\mu \sin\delta \\ \nu_2 &= -\nu_e \sin\delta + \nu_\mu \cos\delta \end{aligned}\right\} \quad (\delta:\text{real}) \tag{2}$$

In terms of the true neutrinos, (1) is expressed as

$$j_\lambda = (\bar{e}\nu_1)_\lambda \cos\delta + (\bar{\mu}\nu_1)_\lambda \sin\delta - (\bar{e}\nu_2)_\lambda \sin\delta + (\bar{\mu}\nu_2)_\lambda \cos\delta. \tag{1'}$$

If $\nu_1$ and $\nu_2$ are regarded as the basic particles together with $e$ and $\mu$, we can construct various models for baryons by generalizing the Nagoya model.

II. 1. One of the most simple models may be given under the assumption that the $B^+$-matter can bind to $\nu_1$ to form a proton but cannot bind to $\nu_2$; $p = \langle \nu_1 B^+ \rangle$, $n = \langle e^- B^+ \rangle$, $\Lambda = \langle \mu^- B^+ \rangle$. ($\langle \nu_2 B^+ \rangle$ corresponds to no baryon).
The baryonic weak current $\langle j \rangle_B$ obtained from (1′) takes the form:

$$\langle j \rangle_B = (\bar{n}p)_\lambda \cos\delta + (\bar{\Lambda}p)_\lambda \sin\delta\,. \tag{3}$$

The weak interaction Hamiltonian is obviously

$$H_\omega = \frac{G}{\sqrt{2}} J_\lambda J_\lambda^+ \tag{4}$$

with

$$J_\lambda = j_\lambda + \langle j_\lambda \rangle_B\,.$$

Remarkable is that the form of (3) can be identified with that of a modified current suggested by Gell-Mann and Lévy [5]:

$$(\bar{n}p)_\lambda \frac{1}{\sqrt{1+\epsilon^2}} + (\bar{\Lambda}p)_\lambda \frac{\epsilon}{\sqrt{1+\epsilon^2}}\,, \tag{5}$$

in which the value of the parameter $\epsilon$ is to be taken as $\sim 1/5$ so as to fit the slow rate of the leptonic decay of hyperons and, at the same time, to explain a subtle difference of $G_v$'s between $\beta$- and $\mu$-$e$ decays. Thus a phenomenological expression (5) can be interpreted as a natural consequence of our scheme by assuming $\sin\delta \sim 1/5$.

II. 2. Relation to the problem of mass difference between $e$ and $\mu$.

There may arise several questions on our approach: a) Is there any reason that $\nu_2$ can do nothing with $B^+$? b) Under what conditions should the angle $\delta$ be determined? As for the question a), we have at present no answer, but we have an analogous situation in the *V-A* interaction, where only half of the 4-components of neutrinos are allowed to interact. On the contrary, we may add some remarks about the problem b). Now, let us start with bare leptons (*urleptons*) $\psi_0 = \begin{pmatrix} \mu_0 \\ e_0 \end{pmatrix}$ and $\phi_0 = \begin{pmatrix} \nu_{\mu 0} \\ \nu_{e0} \end{pmatrix}$ whose mechanical masses are zero. The leptonic weak current is defined by

$$j_\lambda = (\bar{\psi}_0 \phi_0)_\lambda\,. \tag{6}$$

We assume here that "urleptons" obey an interaction with a new kind of field $X$ of some large mass. To be more specific, we take an example

$$\mathscr{L}_{\text{int}} = [(\bar{\psi}_0 \Lambda^1 \psi_0) + (\bar{\phi}_0 \Lambda^0 \phi_0)] X^* X \tag{7}$$

with

$$\det \Lambda^1 = \det \Lambda^0 = 0\,. \tag{8}$$

Without loss of generality, matrices $\Lambda^1$ and $\Lambda^0$ can be expressed as

$$\Lambda^1 = \begin{pmatrix} \eta_1^2 & \eta_1\,\eta_2 \\ \eta_1\,\eta_2 & \eta_2^2 \end{pmatrix} \qquad \Lambda^0 = \begin{pmatrix} \eta_1'^2 & \eta_1'\,\eta_2' \\ \eta_1'\,\eta_2' & \eta_2'^2 \end{pmatrix}. \tag{9}$$

To take an intrinsic difference between ($\mu_0$, $e_0$) and ($\nu_{\mu 0}$, $\nu_{e0}$) into account, we choose specifically $\eta_1' = \eta_2' = \eta'$ and regard $\eta'$ to be very small (but not zero). Apparently our system can be diagonalized in terms of new fields (*true leptons*) defined by the transformation:

$$\psi_0 \to \psi = \begin{pmatrix} \mu \\ e \end{pmatrix} \quad \begin{aligned} \mu &= (\eta_1^2+\eta_2^2)^{-\frac{1}{2}}(\eta_1\mu_0 + \eta_2 e_0) \\ e &= -(\eta_1^2+\eta_2^2)^{-\frac{1}{2}}(\eta_2\mu_0 - \eta_1 e_0) \end{aligned} \tag{10a}$$

and

$$\phi_0 \to \phi = \begin{pmatrix} \nu_2 \\ \nu_1 \end{pmatrix} \quad \begin{aligned} \nu_2 &= 2^{-\frac{1}{2}}(\nu_{\mu 0} + \nu_{e0}) \\ \nu_1 &= -2^{-\frac{1}{2}}(\nu_{\mu 0} - \nu_{e0}) \end{aligned} \tag{10b}$$

That $X$ interacts only with $\mu$ and $\nu_2$ is seen by rewriting (7):

$$\mathscr{L}_{\text{int}} = [(\eta_1^2+\eta_2^2)\bar{\mu}\mu + 2\eta'^2 \bar{\nu}_2 \nu_2] X^* X\,. \tag{11}$$

Let us now fix the value of $\eta_1$, $\eta_2$ and $\eta'$. Clearly, $\eta_1^2+\eta_2^2$ can be determined by the condition that the self energy of $\mu$ due to the interaction (11) should correspond to the observed mass of $\mu$. To determine $\eta_1$, $\eta_2$ separately, we assume in the lowest order perturbation, that the diagonal part of the self energies corresponding to the "mass" of $e_0$ and $\mu_0$

takes, in Nambu's unit ($\alpha^{-1}m_e$), the values 1/2 and 1 respectively. Then we have at once a relation $m_\mu = 1+{}^1/_2 = 3/2 \approx 206\ m_e$. It is interesting to notice that our choice of $\eta_1$ and $\eta_2$ is found to be quite favourable in constructing the baryonic weak current. To see it, put

$$\cos(\pi/4+\delta) = \eta_1(\eta_1^2+\eta_2^2)^{-\frac{1}{2}} \tag{12}$$

then the leptonic current (6) again takes the form (1′) and the magnitude of $\delta$ becomes

$$\sin\delta\cos\delta \sim -1/6 \tag{13}$$

as we expected in II. 1. Finally we re-define *weak neutrinos* by the relation:

$$\begin{aligned} \nu_e &= \nu_1 \cos\delta - \nu_2 \sin\delta \\ \nu_\mu &= \nu_1 \sin\delta + \nu_2 \cos\delta \end{aligned} \tag{14}$$

In the present case, however, weak neutrinos are *not stable* due to the occurrence of virtual transition $\nu_e \leftrightarrow \nu_\mu$ caused by (11). If $|m_{\nu_2} - m_{\nu_1}| \sim$ a few MeV, the transmutation time $T$ is $\sim 10^{-18}$ sec. Therefore, a chain of reactions such as $\pi^+ \to \mu^+ + \nu_\mu$, $\nu_\mu$+nucleus→nucleus+($\mu$ and/or $e$) is useful to check the two-neutrino hypothesis only when $|m_{\nu_2} - m_{\nu_1}| < 10^{-6}$ MeV.

## III. A POSSIBLE MECHANISM OF DECAY PROCESSES WITH $\Delta S/\Delta Q = -1$

Experimental results obtained by Fry *et al.*[6] seem to suggest the existence of $K_{e3}$ process with $\Delta S/\Delta Q = -1$:

$$K_0 \to \pi^+ + e^- + \bar{\nu}, \tag{15}$$

which is forbidden in the original scheme of the Nagoya model since the $B$-matter had been assumed never to transfer from one lepton to another. To overcome this difficulty we introduce here a new set of rules for minimal generalization of the model so as to allow this process to occur. As is easily observed, there are two kinds of transfer of $B$-matter. The first is the *leap* from one vertex of weak current to another, e.g. an interaction of the form $(\bar{n}\nu_1)_\lambda(\bar{\nu}_1\Lambda)_\lambda$ obtained from $(\bar{e}\nu_1)_\lambda(\bar{\nu}_1\mu)_\lambda$. The second is the *jump* from one leptonic line to others, made irrespective of weak interactions, such that

$$\mu^- + n(=\bar{e}B^+) \to \Lambda(=\mu^- B^+) + e^-.$$

Clearly, each of these transfers should not occur by itself. But there remains a possibility of admitting the transfer subject to *the rule* ($A$): $B^+$ cannot leap but can jump if induced by another $B^+$ which is present in the baryonic weak current (the induced jump).

By using the two neutrino scheme developed in § 2, a damping factor $P$ associated with the induced jump may be estimated to be

$$P \approx 0.3 \sin\delta = 0.05 \sim 0.1 \tag{16}$$

A crucial test of this mechanism is to detect the decay $K^0 \to \pi^+ + \mu^- + \bar{\nu}$ which is a process with $\Delta S/\Delta Q = -1$, but *forbidden* in the lowest order of weak interaction. Under the rule ($A$), we meet with unfamiliar processes: $K^{+0} \to \pi^{+0} + \mu^+ + e^-$ (or $\pi^{+0} + \bar{\nu}_\mu + \nu_e$). If it becomes clear that these processes are highly suppressed, we must further add *the rule* ($B$): there should be no induced jump between ($\mu$, $e$)- and ($\nu_\mu$, $\nu_e$)-families. The rules ($A$) and ($B$) are sufficient to provide a consistent explanation for the process (15). Although our rules are only of phenomenological nature, one can fix the effective 6-body weak interaction; the $\Delta S/\Delta Q = -1$ part of this interaction is uniquely determined to be

$$\alpha(\bar{p}n)_\lambda[(\bar{\Lambda}\nu_\mu)(\bar{e}n)]_\lambda + \text{h.c.}, \tag{17}$$

where $[(\bar{a}b)(\bar{c}d)]_\lambda$ denotes some vector (and axial vector) quantity, the simplest form of which is $(\bar{a}b)_\lambda(\bar{c}(\alpha+\beta\gamma_5)d)$.

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## DISCUSSION

MARSHAK: You know of course that, if you introduce the $B$-field to give you a sufficient coupling to construct the baryons from the leptons, then the weak decays are much too strong. How do you look at this now?

MAKI: As far as we described $B^+$ as a kind of boson field, we meet with the difficulty you just mentioned. We think rather that $B^+$ cannot be described by a conventional quantized field.

MARSHAK: The second point is connected with the baryon-lepton symmetry principle. As you realise, I would like very much to maintain this principle with 2 neutrinos, but I don't see how your attempt really helps.

FEINBERG: If you accept the evidence for $\Delta S = -\Delta Q$, on the basis of the experiment of Fry *et al.*, then one has an argument that the decay $K^0 \to \pi^+ + e^- + \nu$ must involve the same neutrino as the decay $\overline{K^0} \to \pi^+ + e^- + \bar{\nu}$, because otherwise one would not get the interference phenomenon that actually is found in the experiment. Therefore I think if you are proposing that it is a muon-neutrino that occurs in $\Delta S = -\Delta Q$ decays with an electron, and an electron-neutrino which occurs with an electron in the $\Delta S = +\Delta Q$ decays, then in fact you do not explain Fry's experiment.

THIRRING: It seems to me that the second neutrino does not generate a new difficulty for the correspondence of leptons and baryons. It rather removes one difficulty, because up to now, so to speak, the neutrino was only half of a Dirac particle. Now, since the second half is found, it seems convenient to combine them and you have a correspondence of three particles to three particles.

MARSHAK: This was my first thought as soon as I heard about the two neutrinos. But the trouble is that you have to worry about the conservation of lepton number and also retain positive chiralties for the two neutrinos. If you try some scheme like that of Iso, and take a four component neutrino and let the electron neutrino be the positive chirality part, and the neutrino be the charged conjugate of the negative chirality part, then you have to associate the second neutrino with $\mu^+$. Then, if you associate $\mu^+$ with $\Lambda$, you have forsaken the baryon-lepton symmetry principle.

MARX: You must have interference effects in the neutrino absorption experiments if you have two masses but if the oscillation is very short, you have no possibility to distinguish the two neutrinos; so you can have some experimental possibility to get a limit for that mass difference.

WEINBERG: The upper limit on the mass difference comes out to be something like 3 Volts though. Also, the $\mu \to e + \nu$ experiment would be another place to derive another upper limit, because the existence of a matrix element between $\nu_e$ and $\nu_\mu$ would give a non-zero decay rate.

YAMAGUCHI: Yes, I agree. According to the Nagoya Group, the mass difference is something like 1 eV. As for the second point it is true, that the decay $\mu \to e + \nu$ exists, but you can manage your theory so that this is sufficiently slow, not to disagree with experiment.

SUDARSHAN: While we are all looking for different particles, is there a second kind of muon? In other words is the $K$-meson muon the same as the $\pi$-meson muon?

FEINBERG: I believe the answer to the question is that there is only one muon. The argument is the following: there exist experiments on producing muon pairs by photons which are in agreement with the Bethe-Heitler formula by a few percent. If the $K$-muon and the $\pi$-muon were different then the total cross-section would be twice as great since the cross section for producing each type depends only on its charge, and so is given by the Bethe-Heitler formula and the total cross section would be the sum of the two.

# GAUGE INVARIANCE AND VECTOR FIELDS

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Recently the possibilities of constructing theories of elementary particles by analogy with electrodynamics have been extensively discussed. The notion of gauge invariance plays an important role in such theories (papers of Yang and Mills, Utiyama, Sakurai, Salam and Ward, Gell-Mann and Glashow and others [1-22]). The characteristic feature of gauge theories is a deep parallel in treatment of, for example, baryon and electric charges.

The present report is devoted to the discussion of gauge invariance (G.I. below) and some other problems, concerning electrodynamics and similar theories.