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REMARKS ON TRIPLET MODELS IN SU_3 SYMMETRY ^{*)}T.D. Lee ⁺⁾

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A B S T R A C T

Assuming that (i) the charges of all particles are integral multiples of the same unit and (ii) all known strongly interacting particles can be regarded as composites of two basic particles, a triplet α and a singlet (or a triplet) β , through their strong interactions which are approximately SU_3 invariant, many different models can be constructed. It is shown that from a phenomenological point of view, all these models can be regarded as equivalent to each other. The stability question whether a single α is stable against decay into known particles is studied. The stability of α holds if the baryon number of proton is three times that of α . Alternative reasons for expecting stability of α , that are independent of its baryon number assignment, are presented. Speculations connecting the possible existence of such stable particles in the universe and the many recently observed violent outbursts in various galaxies are outlined.

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1. INTRODUCTION

The recent successes in applying the idea of SU_3 symmetry ^{1),2)} to strong interactions have led many authors ^{3),4)} to suggest that the underlying mechanism of this approximate symmetry is connected with the possible existence of a basic massive triplet which can be regarded as the base vectors for a (3×3) irreducible representation of the SU_3 group, and whose interactions are approximately invariant under the same SU_3 transformation. The simplest model is the one proposed by Gell-Mann and Zweig ³⁾, in which all known strongly interacting particles are assumed to be composites of a single triplet (called Quarks or Aces) and its antiparticles. It is found that the charges of the quarks must be $2e_Q$, $-e_Q$ and $-e_Q$ where e_Q is related to the observed charge of the proton e_p by

$$e_p = 3e_Q. \quad (1)$$

Similarly,

$$N_p = 3N_Q \quad (2)$$

where N_p and N_Q are the baryon numbers of proton and quark, respectively. Equations (1) and (2), by themselves, present no difficulty since p is a composite made of three quarks. However, in the same model, the leptons which have no strong interactions are not composites of the quarks. Both the leptons and the quarks are regarded as fundamental particles. It appears strange that the basic unit of charge e_ℓ for the leptons should be three times that of the quarks,

$$e_\ell = 3e_Q \quad (3)$$

which is difficult to understand if the electron or the muon is believed to be a fundamental particle.

In this paper, we shall follow a different approach by assuming that :

- i) the charges of all particles must be integral multiples of the same unit e , and
- ii) all known strongly interacting particles can be regarded as composite of a basic triplet (called α 's) and another set of particles (called β 's), which also belong to an irreducible representation of the SU_3 group.

The simplest solution is to assume the β to be a singlet. Other solutions also exist which correspond to β being a triplet, or other multiplet. In the next Section we shall analyze the properties of these solutions, and show that all these different solutions are related through a simple transformation. From a phenomenological point of view, these different solutions can be regarded as equivalent to each other.

It is obvious that a single α cannot decay into a final state consisting of only the presently known strongly-interacting particles through the very strong SU_3 conserving interaction. For the SU_3 non-conserving strong interaction h , the same stability holds if h is assumed to transform like a member of an octet under SU_3 . In Section 3, it is shown that the alternative assumption that h transforms like a member of a triplet must be ruled out if the isoscalar member of the α 's is charged. The simplest charge assignment for the α 's is $(0, -e, -e)$. In Section 4, it is shown that if in weak interaction the current of the strongly interacting particles is assumed to belong to a single irreducible representation of the SU_3 group, then the same stability condition must also hold for the weak interaction.

An alternative and, perhaps, more appealing possibility for expecting stability of α independent of its charge assignment is to assume the baryon number of proton to be three times that of α .

The possibility that there might exist a new stable massive particle has some far-reaching consequences. In Section 5, we give some estimations of the limits on the abundance of such a stable particle on earth, in cosmic rays and in galaxies. It is speculated that their presence in our universe may provide a new mechanism to explain the many recently observed violent outbursts in various galaxies ⁵⁾.

2. REVIEW OF MODELS

From our assumption ii), all known strongly interacting particles are considered to be composites of these basic α 's and β (or β 's) through their strong interactions which are approximately invariant under SU_3 . So far as the transformation properties of these known particles are concerned, we can regard the known mesons (pseudoscalar or vector) and the spin $\frac{1}{2}$ baryon octet B as

$$\text{Meson} = (\bar{\alpha} \alpha) \quad \text{or} \quad (\bar{\beta} \beta) \quad (4)$$

and

$$B = [\beta \times f(\alpha, \bar{\alpha})] \quad (5)$$

where f is a function of α and $\bar{\alpha}$. In the case of $\beta = \text{triplet}$, Eq. (5) differentiates β from α . By making a definite choice of the function f in Eq. (5), these two conditions determine many properties of the model. Several examples of these models are listed in the Table.

These different models can be easily related to each other. For example, model I' becomes the same as model I (so far as the quantum numbers are concerned) if we identify

$$(\beta)_{I'} = [\beta(\alpha^i \alpha^j \alpha^k \epsilon_{ijk})]_I \quad (6)$$

and

$$(\alpha_i)_{I'} = (\alpha_i)_I \quad (7)$$

where the subscript I and I' denote the model, $i, j, k = 1$ or 2 or 3 and $\epsilon_{ijk} = +1$ or -1 or 0 , depending on $(i, j, k) = \text{even or odd permutations of } (1, 2, 3)$, or otherwise.

Throughout the paper, we use α_i to denote symbolically the appropriate i^{th} particle α in an arbitrary momentum state, and α^i its antiparticle $\bar{\alpha}$. All repeated indices are to be summed over. Similarly, models II and II' are related to I by :

$$(\beta_i)_{\text{II}} = (\beta \alpha_i)_I, \quad (8)$$

$$(\alpha_i)_{\text{II}} = (\alpha_i)_I \quad (9)$$

and

$$(\beta_i)_{\text{II}'} = (\beta \alpha^j \alpha^k \epsilon_{ijk})_I, \quad (10)$$

$$(\alpha_i)_{\text{II}'} = (\alpha_i)_I. \quad (11)$$

Furthermore, the two choices of different statistics for the α 's in model I can also be related to each other through

$$(\alpha_i)_{\text{IF}} = (\beta \alpha_i)_{\text{IB}}, \quad (12)$$

and a corresponding shift of the baryon number n of the α 's,

$$(n)_{\text{IF}} = (n)_{\text{IB}} - 1, \quad (13)$$

where the indices IF and IB denote, respectively, the cases when α = Fermion and α = Boson in model I.

From a phenomenological point of view, these different models appear to be identical. Starting with, say, model I, states such as $(\beta \alpha^i \alpha^j \alpha^k \epsilon_{ijk})$, $(\beta \alpha_i)$, etc., certainly exist. Most of these states (which may include β itself) will lie in a continuum. Lacking a complete (and calculable) theory of strong interactions, it is almost impossible to differentiate these different models⁶⁾. On the other hand, as we shall see, different choices of q and n can lead to quite different physical consequences.

3. STABILITY IN STRONG INTERACTIONS

To be definite, we assume the Hamiltonian for the strong interaction to consist of two parts :

$$H_{\text{strong}} = H + h \quad (14)$$

where H is invariant under SU_3 and h is not. Furthermore, we shall assume H_{strong} depend only on the field operators of α , $\bar{\alpha}$ and β , $\bar{\beta}$.

Through the SU_3 conserving interaction H alone, it is clear that the selection rule

$$\alpha \not\rightarrow \text{known particles} \quad (15)$$

holds. To study this selection rule in the presence of the SU_3 symmetry violating interaction, transformation properties of h have to be used. This selection rule (15) can be valid in any SU_3 non-conserving interaction, provided the interaction is invariant under a particular SU_3 transformation u which changes

$$\alpha_j \rightarrow \exp(i2\pi/3) \alpha_j, \quad (16)$$

for all j . If an interaction is invariant under Eq. (16), it is also invariant under the group Z_3 , the centre of SU_3 , which contains three elements : 1, u and u^2 .

In order to derive the known Gell-Mann - Okubo mass formulae ⁷⁾, we must assume that

$$H \gg h,$$

and the lowest order contribution of h to the mass formulae transforms like the isoscalar member of an octet. There are two simple possibilities (apart from a possible additive SU_3 invariant term) :

$$i) \quad h = (h)_8, \quad (17)$$

or

$$ii) \quad h = (h)_3 + \text{Hermitian conjugate} \quad (18)$$

where the subscripts 3 and 8 denote whether h belongs to a triplet or an octet. These two are the only possibilities, if we make the assumption that h must belong to a simple irreducible representation of the SU_3 group.

In the first case, h is invariant under Z_3 , and selection rule (15) remains valid. In the second case, h is not invariant under Z_3 ; therefore, selection rule (15) is not valid. The observed mass differences between the known particles are due to the second order perturbation $(h \times h)$ whose matrix elements for the relevant mass operator behave like Eq. (17). Thus, one obtains the same mass formula.

Theorem

For the models discussed in the previous Section

$$(h)_3 = 0 \quad (19)$$

provided $q \neq 0$ where q = charge of α_3 in units of e .

Proof

We need only to consider model I. Let F be an arbitrary product function of the field operators for the particles α , $\bar{\alpha}$ and β , $\bar{\beta}$. By using the Table, it can be shown that

- i) if F is invariant under SU_3 , then the charge Q associated with F must be of the form

$$Q(F) = p(3q + 1), \quad (20)$$

where q is, by definition, an integer and p is also an integer (+, - or 0);

- ii) if F transforms like the third member of a triplet, then

$$Q(F) = \pm q + p(3q + 1) \quad (21)$$

where the $\pm$ sign depends on whether the triplet belongs to the representation 3 or $\bar{3}$. Equation (21) is a consequence of i) and the fact that F must be of the form $\alpha_3 \times$ invariant, or $\alpha^i \alpha^j \in \bar{3}_{ij} \times$ invariant, or their conjugates.

All strong interactions must conserve isotopic spin. Thus, $(h)_3$ must be the third (i.e., isoscalar) member of a triplet. From charge conservation, we have

$$Q[(h)_3] = 0. \quad (22)$$

This, together with Eq. (21), implies that if $(h)_3 \neq 0$ then $p = q = 0$, which establishes the theorem.

If $q \neq 0$, the second possibility $h = (h)_3$ must be discarded. We are left with the first case, which allows the validity of Eq. (15) in all strong interactions. The simplest choice is

$$q = -1 \quad (23)$$

which corresponds to charges 0, -e, -e for α_1 , α_2 and α_3 , respectively. Assuming the usual form of minimal electromagnetic interactions, selection rule (15) is also valid in the electromagnetic interactions.

Remarks

- i) The above discussions remain the same, if we include in Eqs. (17) or (18) an additional SU_3 invariant term.
- ii) If $q \neq 0$, selection rule (15) can be violated if one adds to (17) a further term, say a sextet member $(h)_6$, but with not too big a magnitude so as not to upset the known mass formula.
- iii) If $q \neq 0$, selection rule (15) can also be violated if one considers a more complicated case in which some of the general bases of our models are being changed. For example, there exists, in addition to the α and β , other different kinds of particles, such as another singlet boson β' with charge = e and baryon number = 0.
- iv) Independent of the value of q , selection rule (15) must be valid in all interactions (including weak interactions) if the baryon numbers N_p and N_α are related by

$$N_p = 3N_\alpha \quad (24)$$

The transformation (16) becomes a special baryon number gauge transformation. Unlike Eq. (3), relation (24) presents no difficulty. For example, in model I' the baryon number of β is zero, and it is quite natural to find the compound $p = \beta (\alpha \alpha \alpha)$ to satisfy Eq. (24).

- v) It also could happen that $q = 0$ and $N_\alpha = \text{integer} \times N_p$, but $\mathcal{H}$ remains invariant under Z_3 ; e.g., $\mathcal{H}$ is given by Eq. (17).

4. STABILITY IN WEAK INTERACTIONS

To make our analysis definite we shall generate the effective Lagrangian for the weak interaction by introducing a hypothetical intermediate boson W .

[The same conclusion can, of course, be reached by using the appropriate sum of (current) $\times$ (current) scheme without W .] The Lagrangian for the interaction of the charged $W^\pm$ can be written as

$$W_\lambda J_\lambda + W_\lambda j_\lambda + \text{h.c.} \quad (25)$$

where W_λ is the field operator for the intermediate boson, J_λ the current of α and β , and j_λ that of leptons. The effective second order Lagrangian for processes without W is

$$\mathcal{L}_{\text{eff}} = J_\lambda^* J_\lambda + j_\lambda^* j_\lambda + J_\lambda^* j_\lambda + j_\lambda^* J_\lambda \quad (26)$$

plus other terms due to possible neutral W fields. All observed weak interactions are compatible with the assumption that ⁸⁾

$$J_\lambda = (J_\lambda)_8 \quad (27)$$

where $(J_\lambda)_8$ belongs to an octet. If Eq. (27) holds, then selection rule (15) is valid in weak interactions.

It is easy to see that the alternative choice

$$J_\lambda = (J_\lambda)_3, \quad (28)$$

where $(J_\lambda)_3$ transforms like a triplet under SU_3 , leads to incorrect consequences. Substituting Eq. (28) for Eq. (26), one finds that in the Born approximation the leptonic decays of the known strongly interacting particles cannot occur, while

all other decays are allowed. Leptonic decays of $K, n,$ etc., can occur by using Eq. (26) twice. However, these decays would contain many unobserved modes, such as four leptonic decay modes and neutral leptonic decay modes of known particles. Therefore, $J_\lambda \neq (J_\lambda)_3$. Similarly, $J_\lambda \neq (J_\lambda)_6$ where $(J_\lambda)_6$ transforms like a sextet under SU_3 , etc.. It is, of course, not possible to rule out the complicated possibility that in addition to Eq. (27) there is, for example, a small triplet term $(J_\lambda)_3$ which has little to do with the presently observed weak interactions, but can violate the selection rule (15).

In the above discussions, we have demonstrated the possibility that selection rule (15) could be valid in all interactions, and that under certain circumstances this possibility seems to be also the only one. If we make the ad hoc assumption that the current J_λ must belong to a single irreducible representation of SU_3 , then the weak interaction must be invariant with respect to the group Z_3 . Similarly, if the SU_3 non-invariant part h of the strong interaction is assumed to belong to a single irreducible representation, then h must be also Z_3 invariant provided $q \neq 0$. The alternative possibility which necessitates Z_3 invariance independent of charge assignment, is to assume Eq. (24). While none of these can be regarded as compelling reasons, the many practical consequences which follow from the validity of Eq. (15) make the important difference between these possibilities and all other cases.

We shall assume, in the following, that all interactions are invariant under Z_3 . Therefore, there must exist at least a new massive stable particle which corresponds to one with the smallest rest mass among all states belonging to the thrice-valued representations, such as $3, \bar{3}, 6, \bar{6}$, etc., of the group SU_3/Z_3 . For simplicity, we shall assume this stable particle to be one of the α 's and that $q = -1$.

If the isospin singlet α_3^- has lower mass than the isospin doublet (α_1^0, α_2^-) , the two stable particles are α_3^- and $(\bar{\alpha}_3)^+$. If α_3^- has a higher mass than the isospin doublet, the stable one can be either α_2^- or α_1^0 . Depending on the sign of their mass difference Δ , either

$$\alpha_1^0 \rightarrow \alpha_2^- + e^+ + \nu_e, \quad (29)$$

or

$$\alpha_2^- \rightarrow \alpha_1^0 + e^- + \bar{\nu}_e, \quad (30)$$

would occur. The magnitude of Δ is expected to be rather small (perhaps ~ 10 MeV). The decay rate for either Eqs. (29) or (30) is estimated to be $\sim 40 \times \Delta^5 \text{sec}^{-1}$ where Δ is in units of 10 MeV.

In any case, a long-lived charged particle is expected. Detection of such a particle either by using a sufficiently high-energy accelerator or in cosmic rays would be of great importance.

5. ABUNDANCE OF STABLE α 's

From the accuracy of the known mass formulae, the mass of α may be estimated to be of the order of 10 GeV. The α 's can be produced in pairs by a cosmic-ray proton with an energy > 250 GeV,

$$p + p \rightarrow \alpha + \bar{\alpha} + \dots \quad (31)$$

By using the flux of primary protons ⁹⁾ and a cross-section $\sim (\text{mass of } \alpha)^{-2}$ for Eq. (31), the flux of α can be estimated to be about 10^{-1} /sterad/cm²/year due to its production in atmosphere. A much smaller flux of α 's is expected in the primary cosmic rays if the removal mechanism of the energetic primary protons is largely due to leakage from the galaxy.

Because of its strong interaction, the mean free path of an α in matter is about the same as the geometrical nuclear mean free path. After stopping, the α 's will be redistributed ¹⁰⁾ over the surface of the earth because of mountain formation, ocean flow, etc.. As a result of cosmic rays through the lifetime of earth an over-all concentration of $\approx 10^5$ α 's per cm³, can be accumulated on the surface of the earth. Such a small concentration is certainly compatible with any limits that can be set by using other observations. The most severe limit is perhaps to assume that $(\bar{\alpha})^+$ is stable. An $(\bar{\alpha})^+$ behaves like a heavy isotope of hydrogen. A cursory survey of the literature ¹¹⁾ indicates that only an upper limit $\sim 10^{-10} \times (\text{abundance of H})$ can be put on the abundance of $(\bar{\alpha})^+$ on the surface of the earth.

It seems reasonable to expect that any stable particle should be present (or produced) with some abundance in the early evolutionary period of our universe. Unlike p and $\bar{p}$, or e^- and e^+ , large amounts of α and $\bar{\alpha}$ can coexist within the same galaxy, provided the α -enriched regions (i.e., regions containing α , p and e^-) are separated from the $\bar{\alpha}$ -enriched regions (i.e., regions containing $\bar{\alpha}$, p and e^-) by the normal regions which contain only p and e^- .

If the linear dimensions of the normal regions are sufficiently large, and since

$$\alpha \text{ (or } \bar{\alpha} \text{)} + \text{known particle} \not\rightarrow \text{known particles}, \quad (32)$$

the galaxy evolves in the usual way¹²⁾. Stars formed in the normal regions are just like the normal stars containing only protons and electrons. If α^0 and $\bar{\alpha}^0$ are stable, stars formed in the α -enriched region (or $\bar{\alpha}$ -enriched region) are expected to have the heavy α^0 (or $\bar{\alpha}^0$) mainly in their centres and p, e^- in their outer layers. If α^- and $(\bar{\alpha})^+$ are stable, neutral objects like (α^-p) and $(\bar{\alpha}^+e^-)$ can be formed. Because of the large difference in their sizes, stars formed in the α -enriched region would contain mostly (α^-p) in their centres and p, e^- in their outer layers; stars formed in the $\bar{\alpha}$ -enriched regions would, however, have a relatively uniform composition in $\bar{\alpha}^+, p$ and e^- .

If we assume a total mass of α and $\bar{\alpha}$ to be not much bigger than 10-20% of the total mass of the universe, very little can be concluded from the existing small limit of α (or $\bar{\alpha}$) on the surface of the earth. The only conclusion is that if α^- and $(\bar{\alpha})^+$ are stable, the solar system is not formed in an $\bar{\alpha}$ -enriched region.

An interesting speculation is to consider the special case that the linear dimension of a particular normal region is about or less than a few light years. Because of star formations or other causes, material from its neighbouring α -enriched and $\bar{\alpha}$ -enriched regions may occasionally be brought into contact. The annihilation

$$\alpha + \bar{\alpha} \rightarrow p + \bar{p} + \dots, \quad (33)$$

can stimulate further annihilation processes of $(p+\bar{p})$ which, in turn, would contribute to generate mass motion and result in more mixing of α and $\bar{\alpha}$. Assuming a turbulent velocity $\sim 10^{-2}c$, it is not unreasonable to anticipate a rate of energy release $\sim 10^{-2} \times (\text{mass of sun}) \times c^2$ per year and with a total energy release that can last over $\sim 10^6$ years. Furthermore, because the annihilation processes extend over a few light years, large fluctuation in energy release, over the period of a year, seems again not unreasonable. This new mechanism of energy release may account for the many violent outbursts observed recently in various galaxies ⁵⁾.

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	I	I'	II	II'
Models	$(\alpha_1, \alpha_2, \alpha_3)$ β	$(\alpha_1, \alpha_2, \alpha_3)$ β	$(\alpha_1, \alpha_2, \alpha_3)$ $(\beta_1, \beta_2, \beta_3)$	$(\alpha_1, \alpha_2, \alpha_3)$ $(\beta_1, \beta_2, \beta_3)$
Q/e	$(q+1, q, q)$ 0	$(q+1, q, q)$ $-(1+3q)$	$(q+1, q, q)$ $(q+1, q, q)$	$(q+1, q, q)$ $(-2q, -1-2q, -1-2q)$
I	$(\frac{1}{2}, \frac{1}{2}, 0)$ 0	$(\frac{1}{2}, \frac{1}{2}, 0)$ 0	$(\frac{1}{2}, \frac{1}{2}, 0)$ $(\frac{1}{2}, \frac{1}{2}, 0)$	$(\frac{1}{2}, \frac{1}{2}, 0)$ $(\frac{1}{2}, \frac{1}{2}, 0)$
I _Z	$(\frac{1}{2}, -\frac{1}{2}, 0)$ 0	$(\frac{1}{2}, -\frac{1}{2}, 0)$ 0	$(\frac{1}{2}, -\frac{1}{2}, 0)$ $(\frac{1}{2}, -\frac{1}{2}, 0)$	$(\frac{1}{2}, -\frac{1}{2}, 0)$ $(\frac{1}{2}, -\frac{1}{2}, 0)$
N/N _P	n 1	n $(1-3n)$	n $n+1$	n $1-2n$
Statistics	F	F B	F B	F F
	or B	or B F	or B F	or B F
Spin $\frac{1}{2}$ octet (N = 1)	$(\beta \bar{\alpha} \alpha)_s$	$[\beta(\alpha \alpha \alpha)]_s$	$(\beta \bar{\alpha})_s$	$[\beta(\alpha \alpha)]_s$
Mesons N = 0	$(\bar{\alpha} \alpha)_{1,s}$ $(\bar{\beta} \beta)_1$	$(\bar{\alpha} \alpha)_{1,s}$ $(\bar{\beta} \beta)_1$	$(\bar{\alpha} \alpha)_{1,s}$ $(\bar{\beta} \beta)_{1,s}$	$(\bar{\alpha} \alpha)_{1,s}$ $(\bar{\beta} \beta)_{1,s}$

Table - Examples of different models :

charge = Q, isotopic spin = I, baryon no. = N, F = Fermi statistics, B = Bose statistics. The subscripts 1 and s in $(\bar{\alpha} \alpha)_1$, $(\bar{\alpha} \alpha)_s$, etc., indicate singlet or octet representation. To satisfy assumption (i), q must be an integer (+, -, or 0). By using Eqs. (6) - (13) and from a phenomenological point of view, all these different models are equivalent to each other.

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- 10) I wish to thank Dr. G. Cocconi for pointing out this to me.
- 11) R. Sherr, L.G. Smith and W. Bleakney, Phys. Rev. 54, 388 (1938).
- 12) If α^0 and $\bar{\alpha}^0$ are stable, the mean free path of α in a galaxy is $\sim 3 \times 10^7$ light years, assuming the mean particle density in the galaxy to be ~ 1 per cm^3 . Collisions between α or $\bar{\alpha}$ and other particles (p, α , $\bar{\alpha}$, etc.) become important only through processes such as star formations when the α or $\bar{\alpha}$ encounters matter of a much greater density. The average initial velocity v_α of α^0 and $\bar{\alpha}^0$ is, therefore, an important parameter in determining the evolution of a galaxy. For our simple considerations, we tacitly assume that v_α is not too large; say, less than $\sim 10^5$ cm/sec. The same conclusion applies to the (α^- p) system if α^- and $\bar{\alpha}^+$ are stable.