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HIGHER SYMMETRY SCHEMES FOR STRONG INTERACTIONS

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1. INTRODUCTION

This lecture reviews some of the extensions of SU_3 symmetry which have been proposed in the last year. In many respects, it covers the same subject matter as Salam's excellent report at the International Conference on High Energy Physics at Dubna last August. The very recent and very important developments combining SU_3 and ordinary spin in a SU_6 symmetry scheme will not be discussed here. The main results obtained to date are listed in Matthews' lecture at this meeting, and the difficult problems related to the actual meaning and extent of SU_6 symmetry are currently in a rapid process of discussion and analysis, the conclusions of which are quite unclear at the present time. As to references, we do not attempt to give complete lists, and the papers quoted are usually meant as examples of many publications dealing with the same topics.

2. BASIC SU_3 TRIPLETS, QUARKS

The remarkable success of SU_3 predictions has led many people to speculate about the existence of hadrons (strongly interacting particles) belonging to the basic representations 3 and $\bar{3}$ of SU_3 . It is obvious that there is nothing compelling about the existence of such basic SU_3 triplets, but a discussion of what their properties and implications might be could hopefully lead to further progress. In most speculations of this sort, one has regarded the basic triplets as heavy, perhaps 5 or 10 times heavier than the proton, the known hadrons being bound states of them. This would give a very simple, if perhaps too naïve, explanation of the success of mass formulae valid to first order perturbation theory in the mass splitting operator. It also leads to a novel and most interesting representation of the presently known hadrons as tightly bound states of as yet undiscovered basic particles, the nature of which would have to be revealed by future very high energy experimentation.

2.

If one keeps to the Gell-Mann-Nishijima formula relating electric charge Q in units of e to hypercharge Y and third isospin component I_3

$$Q = I_3 + \frac{1}{2}Y$$

a SU_3 triplet 3 has $Q = \frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}$, and a triplet $\bar{3}$ has the opposite charges. Such fractionally charged particles have been proposed by Gell-Mann ¹⁾ and Zweig ²⁾ under the names of quarks or aces. If they exist, charge conservation implies the existence of at least one absolutely stable particle of fractional charge, and of its antiparticle. The search for such particles has up to now given no positive result. Even if they do not exist, the use of a quark field in theoretical model calculations can be extremely instructive as shown by many recent investigations.

3. BASIC SU_3 TRIPLETS WITH INTEGRAL CHARGE

Let us now discuss the problem of basic SU_3 triplets under the assumption that all particles have integral electric charge, thereby excluding the possibility of quarks. The existence of SU_3 triplets then gives rise to a new additive quantum number D defined by

$$Q = I_3 + \frac{1}{2}Y + \frac{1}{3}D ;$$

it has integral values only. At least four different names have been proposed for it, and we shall refrain from using any of them. The simplest assumption is to take D constant within each SU_3 multiplet, so that $\frac{1}{3}D$ is the average charge of the particles in the multiplet. Known mesons and baryons successfully assigned to SU_3 multiplets have $D=0$. Hence D cannot be a function of the baryon number N and is a quantum number independent of it. Some of the other known hadrons may have $D \neq 0$. Conservation of D may be violated by weak, electromagnetic or even medium strong interactions, so that all $D \neq 0$ particles may be unstable. The combination $Y + \frac{2}{3}D$, however, should be conserved by electromagnetic and strong interactions because Q and I_3 are supposed to have this property.

In contrast to the case of quarks, it is now impossible to regard known hadrons as composite particles built up of one basic triplet t and its antitriplet $\bar{t}$. Let a hadron a have the composite structure $t^n \bar{t}^{n'}$, by which is meant that it is a bound state of n basic particles belonging to t and of n' basic antiparticles of $\bar{t}$. We then have

$$N_a = (n-n')N_t, \quad D_a = (n-n')D_t$$

where $N_{a,t}$, $D_{a,t}$ are the values of N , D for a and t . Let a be a known baryon with $D=0$, the proton for example. From $D_a=0$ we conclude $n=n'$ and hence $N_a=0$ instead of $N_a=1$. Obviously, in the integral charge case here considered, at least one more basic particle u is needed, with either $N_u \neq 0$, or $D_u \neq 0$, or both. The antiparticle $\bar{u}$ is therefore distinct from u . A simple possible choice is to take for u a unitary singlet with $N_u=1$, $D_u=0$; while t would have $N_t=D_t=1$. All known SU_3 multiplets of hadrons are then readily constructed out of the four basic particles t , u and their antiparticles. Many other choices are possible, however, and also the spin of t and u can be selected in various ways. A summary of various possibilities is contained in a recent paper by Lee ³⁾.

In the quark model, the known 0^- and 1^- meson multiplets have the composition $\bar{q}q$ (q = quark) with the SU_3 structure $\bar{3} \times 3 = 1+8$, while the baryon $\frac{1}{2}^+$ octet and $\frac{3}{2}^+$ decuplet are given the common composition qqq with structure $3 \times 3 \times 3 = 1+8+8+10$. Such common structures, both for 0^- and 1^- mesons, and for $\frac{1}{2}^+$ and $\frac{3}{2}^+$ baryons, are very attractive, especially now that work on SU_6 uncovers many similarities between mesons of different spin, and between baryons of different spin. In composite models with integrally charged basic particles, the common structure $3 \times 3 \times 3$ cannot be obtained for the baryon octet and decuplet if one has only the four basic particles t , u considered above. To obtain it one needs two basic triplets t and Θ , Θ and $\bar{\Theta}$ being different from both t and $\bar{t}$. This gives six basic particles t , Θ , and their antiparticles.

4. BASIC PARTICLES AND HIGHER SYMMETRIES

As we have just seen, the assumption of a basic SU_3 triplet t with integral electric charge necessarily leads to the introduction of a new additive quantum number D and to the existence of additional basic particles, u or Θ . It is therefore natural to look for symmetries higher than SU_3 which would incorporate both D and the additional basic particles in a group-theoretical scheme containing also SU_3 and t . This can be done in many ways. In the absence of a priori clues, the most straightforward and in many respects most natural procedure is to explore the possibilities offered by the simple Lie groups of rank three, the third additive quantum number Z defined by the group being a linear combination of D and N . One will naturally try to have the basic particles form the basic representation of the group.

There are three simple Lie algebras of rank three : A_3 , B_3 and C_3 , the corresponding covering groups being SU_4 , the covering group of SO_7 and Sp_6 . The basic representation of SU_4 has the SU_3 contents $4 = 3+1$ and can accommodate a basic SU_3 triplet t and a basic singlet u as considered above. For Sp_6 the basic representation is $6 = 3+\bar{3}$ and accommodates two basic triplets t and Θ . The same is true for $SO_6 = SU_4/Z_2$. For SO_7 it is $7 = 3+\bar{3}+1$, and for the covering group $8 = 3+\bar{3}+1+1$, so that in addition to t and Θ one would have one or two basic singlets. Needless to say, when assuming all basic particles to belong to the basic representation of the rank three group, one supposes that they all have the same value of spin and baryon number.

All groups mentioned above have been studied in the literature. The most obvious one, SU_4 , has been treated by many authors ⁴⁾, and specific models based on Sp_6 ⁵⁾ and SO_7 ⁶⁾ have been investigated. A recent comparative study has been made by Gerstein and Whippman ⁷⁾. It concentrates on the 0^- and 1^- mesons and their interaction. It shows that all groups having two SU_3 triplets in their basic representation, i.e., SO_6 , Sp_6 and SO_7 , give the same results both for mass formulae and the decay widths for $\phi \rightarrow \rho \pi$, $\phi \rightarrow K\bar{K}$, and these results are in excellent agreement with experiment. The corresponding SU_4 predictions, in contrast, are unsuccessful and lead to rejection of the models proposed.

It may also be noted that one model led to a tentative assignment of a particle with $D \neq 0$. It is Sp_6 , in which the O^- meson of mass 960 MeV should be regarded as a superposition of SU_3 singlets with $D = \pm 1$. This then led to the conjecture that the $K \pi \pi$ resonance at 1215 MeV and a possible $\rho \pi$ enhancement at 975 MeV would be pseudoscalar particles and would complete the Sp_6 multiplet of O^- mesons ⁸⁾.

Certain basic particle models have also been considered which lead to other types of higher symmetry groups. The main investigation of this sort is due to Schwinger ⁹⁾ who introduces a fermion triplet with $N=1$ and a boson triplet with $N=2$, transforming under independent U_3 groups, so that the higher symmetry involved has the structure $U_3 \times U_3$. More symmetries of this direct product form will be encountered in the next Section.

5. INTERACTIONS AND HIGHER SYMMETRIES

A different line of speculation leading to higher symmetry groups starts from the current operators playing a role in weak, electromagnetic and possibly strong interactions, and studies the algebras generated by the corresponding charges. For weak currents it was developed in 1962 by Gell-Mann ¹⁰⁾ who considers octets of vector and axial vector currents, $f_{i\alpha}(x)$ and $f_{i\alpha}^5(x)$, $i=1, \dots, 8$; $\alpha=1, \dots, 4$, and the corresponding charges

$$F_i(t) = -i \int f_{i4} d_3x, \quad F_i^5(t) = -i \int f_{i4}^5 d_3x.$$

The $f_{i\alpha}(x)$ are supposed to be the conserved currents following from SU_3 symmetry, so that the F_i are the generators of SU_3 transformations and obey the SU_3 structure equations

$$[F_i(t), F_j(t)] = i f_{ijk} F_k(t)$$

The $f_{i\alpha}^5(x)$ are assumed to belong to a SU_3 octet, hence

$$[F_i(t), F_j^5(t)] = i f_{ijk} F_k^5(t).$$

One then closes the algebraic system of the 16 operators F_i, F_i^5 by postulating

$$[F_i^5(t), F_j^5(t)] = i f_{ijk} F_k(t).$$

The Lie algebra thus obtained belongs to the group $SU_3 \times SU_3$, as is immediately seen by noticing that the commuting sets of operators

$$F_i^\pm = \frac{1}{2} [F_i \pm F_i^5]$$

verify the SU_3 structure equations. This enlarged symmetry scheme can be broken or extended in various ways ¹¹⁾, and also ordinary spin can be incorporated in it ¹²⁾.

Also strong interactions lead to possible higher symmetries, as shown for example in the early work of Marshak and Okubo ¹³⁾. The success of SU_3 symmetry has encouraged fresh investigations of these possibilities. Following Salam and Ward ¹⁴⁾, one can remark that SU_3 generates only currents which give F type coupling, whereas D type coupling is known to be important (the F/D ratio is of order 1/3 for pion-nucleon interactions). Assuming a $SU_3 \times SU_3$ transformation group for the baryon octet

$$\psi_{\beta}^{\alpha} \rightarrow \sum_{\alpha' \beta'} U_{\alpha'}^{\alpha} \psi_{\beta'}^{\alpha'} U_{\beta}^{\beta'}$$

eight additional vector currents are generated, both F and D coupling being present. Finally, one can combine the two preceding extensions by applying the above procedure twice, once on the left-handed components

ψ_L of ψ and once on the right-handed components ψ_R

$$\psi_L = \frac{1}{2}(1 + \gamma_5)\psi, \quad \psi_R = \frac{1}{2}(1 - \gamma_5)\psi.$$

The resulting group is $SU_3 \times SU_3 \times SU_3 \times SU_3$, and the 32 generators will give octets of vector and axial vector, F and D type currents ¹⁵⁾.

It seems difficult to say at present which of these many possibilities will be most relevant to order the physical facts. It should be noted in this context that the $(SU_3)^2$ and $(SU_3)^4$ schemes involving both vector and axial vector currents connect systems of opposite parities, and indeed several authors have predicted along these lines 0^+ and 1^+ mesons which would parallel the well-known 0^- and 1^- particles. It is interesting that also bootstrap calculations lead to such parity doubling of mesons ¹⁶⁾. Experimentally, it is nevertheless disturbing that while some 1^+ mesons are already known, the existence of scalar particles has never been established ¹⁷⁾.

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