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Yao-yang Liu is the earliest discoverer of the "colors" of quarks

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Abstract

We review briefly the various stages in the history of the discovery of the color degree of freedom. It is pointed out that there has been a article which was published in a Chinese Journal in 1966 where the colored quark model was proposed. The evidences give credit to that Yao-yang Liu is the earliest discoverer of the colors of quarks.

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The purpose of elementary particle physics is to find the fundamental structure of matter and the laws that govern these objects. Quarks are recognized today as being the elementary building blocks of which matter is constructed. In the search for the quark model, physicists have won tremendous successes through all difficulties. Most of the important contributions of the physicists have been brought into public notice. Maybe there is no one today who thinks that the first-class contribution to particle physics could been covered. But in fact, the discovery of the "color" degree of freedom of quarks, the brilliant work of Professor Yao-yang Liu, has been covered over the past 27 years. In 1966, Liu proposed a colored quark model which treats a quark as a real ordinary Fermi-Dirac particle with three new quantum numbers, i.e. "colors". Liu's article named " A Possible Model of Elementary Particle"[1] was published in "Atomic Energy", a Chinese Journal (An English transtation of the paper see Appendix). As that we will see the concept of color was earliest definitely introduced in the paper.

The background of Liu's work

The idea of that the elementary particles have a structure can be traced back to 1949. In the year, Enrico Fermi and Chen-ning Yang proposed a theory to describe the structure of the hadrons. Fermi-Yang model treats Pion menson found in 1947 as a very strongly bound nucleon-antinucleon system. In other words, proton(P), neutron (N) and their antiparticles are assumed as constituent particles of the hadron Pion in the Fermi-Yang theory. This is an isospin SU_2 symmetry theory as we called.

After the discovery of strange hadrons such as $K^{\mp}$, K^0, $\bar{K}^0$ and Λ and so on, the rational strangeness of the strange particles is recognized, and the Gell-Mann-Nishijima relation among the baryon number, isospin, charge and strangeness carried by each hadron is summarized. Considering the existence of above hadrons and the Gell-Mann-Nishijima relation, Shoichi Sakata expanded the Fermi-Yang model. He introduced a third symmetry element having spin 1/2, isospin 0, baryon number 1 and strangeness of -1. He identified this element with the baryon Λ, forming with the neutron and proton, the Sakata triplet (P, N. Λ). This triplet of elements has the right quantum numbers for constructing most hadrons. In mathematical language, the symmetry among three elements in the Sakata model is called SU_3 symmetry.

Sakata model arranges the mesons rather well, but for the baryons, especially for a host of the resonance states of baryon number 1, and spin 1/2 and 3/2, the model meets a lot of trouble to explain the growing variety of hadrons.

An alternative scheme of SU_3 symmetry was therefore proposed independently by Murray Gell-Mann and Yuval Neeman in 1961. In this scheme particles with the same spin, with the close mass, and with the strangeness and isospin that obeys the Gell-Mann- Nishijima relation, are grouped together, similar to the "periodic table" of chemical elements. It is well know as the "eightfold way". Using this approach, Gell-Mann and Neeman predicted new particles that were later discovered with appropriate properties. For example, the member of the baryon decuplet, Ω^-, was predicted by this way.

The confirmation of the SU_3 symmetry by the discovery of the particle Ω^- led quickly to the introduction of the quark model. The quark model was introduced independently by Gell-Mann and Geoge Zweig in 1964[2]. Gell-Mann called the triplet of new particles "quarks", and Zweig called them "aces", like the aces in playing cards. Three quarks q are conventionally denoted by u,d, and s. u and d indicate the directions of isospin, up and down; s indicates strangeness. The while, three kinds of quarks, each with electric charge of-1/3, or 2/3, and with the same spin of 1/2, can build all known mesons and baryons. The mesons are states of bound quarks q and antiquarks $\bar{q}$. The baryons are states of three bound quarks (qqq), and the antibaryons are states of three bound antiquarks ($\bar{q}\bar{q}\bar{q}$). These constituent particles are postulated as one layer beyond the known hadrons, and they carry a fractional charge. This is different from the Sakata model.

In order to construct certain representations of the higher symmetry groups to accommodate a great number of the resonances of baryons, and to explore a correlation between spin and SU_3 symmetry, the SU_6 theory was proposed by Feza Gursey and Luigi Radicati, and by Bunji Sakita independently in 1964[3]. Supposing the interaction between quarks is spin and isospin independent, and the excited states (resonances) of the hadrons are in the S state (the orbital angular momentum is zero), then there is a symmetry among the six states of the quark distinguished by the SU_3

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"As mentioned above, we suppose that three classes of quarks have different quantum numbers Z_1, Z_2, Z_3. Each one of the three classes belongs to the fundamental representation of SU_3 or SU_6. Quarks can constitute various representation of SU_6 without violation of Fermi statistics, these quarks can constitute 56-dimension representation provided they belong to different classes"; "In order to assure to give the correct experimental observed quantities of the 56-dimension representation, three classes of quarks must satisfy:

$$Z_1 + Z_2 + Z_3 = 0 \ , \qquad N_1 + N_2 + N_3 = 1 \ ,$$

where N_1, N_2, N_3 represent the baryon numbers of three kinds of quarks respectively".

From the Section III—"The problem of bound state", we abstract that as following:

"As mentioned above, all the observed bound states are zero eigen states of Z, i.e. "neutral" state, there is no interaction among them. Also the bound states are neutral locally, therefore, there is no interaction even between bound state and an individual quark. All of these means that when one put more quark into a bound state only if the additional quarks is one of these bound state its energy can be the lowest one. Then we can understand why all the observed elementary particles are in pair of quark- antiquark or integer times of three".

From above abstract of Liu's work, one can easy grasp its essentials. The new quantum number Z whereat came to be called color later on by Gell-Mann in 1972. The problem of statistics has puzzled physicists for many years, but was overcome in the simple model due to the discovery of colors of quarks. In addition, the Liu colored quark model shown that the quarks come in three colors, but all physical states and interactions are supposed to be singlets of color (i.e. "neutral" states), and that even if there are more than three usual quarks, there are still three colors. These properties of quark and the advantages of the colored model were not recognized by other physicists until 1972. It is worthy to abstract Gell-Mann's work in 1972 in which the "color" was first proposed[6]:

"We take three different kinds of quarks, that is nine altogether, and call the new

variable distinguishing the sets "color", for example red, white and blue (R-W-B). The nine kinds of quarks are then individually Fermi-Dirac particles, but we require that all physical baryon and meson states by singlets under the SU_3 of "color". This means that for the meson $q\bar{q}$ configuration we now have

$$q_R\bar{q}_R + q_W\bar{q}_W + q_B\bar{q}_B$$

and for a baryon qqq we have

$$q_Rq_Wq_B - q_Wq_Rq_B + q_Bq_Rq_W - q_Rq_Bq_W + q_Wq_Bq_R - q_Bq_Wq_R \ ,$$

which is totally antisymmetric in color and permits the baryon to be totally symmetric in the other variables space, spin, isospin and strangeness. This restriction to color singlet states for real physical situations gives back exactly the sort of statistics we want".

It is easy to see that the level of understanding of Liu at beginning of 1966 as well as the one shown above.

Unfortunately, the brilliant work of Liu has been covered. There were several things which accounted for the occurrence. One cause as well know that was due to "the Great Proletarian Cultural Revolution", and here is no need for others to be shown. In a word, the purpose of this paper is to attempt to give the Liu colored quark model a equitable remark.

I should like to thank Professor S. Randjbar-Daemi and his collaborators at the ICTP for their hospitality.

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Appendix

A POSSIBLE MODEL OF ELEMENTARY PARTICLES*

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ABSTRACT

A great number of resonance states have been discovered experimentally, it leads people to believe that the observed elementary particles must have some structure. Gell-Mann suggested a quark model, however there are still some questions needed to be answered if we accecpt it, for example, the saturation of force, statistics, fractional charge etc.. In this paper, we suggest a model by postulating a new quantum number Z and discuss the problems mentioned above. The prelimiary analysis shows that this model meets no significant contradictions with experiments. Finally we make a brief of how this model can be tested in future.

I. INTRODUCTION

The discovery of a great number of resonance states [1] brings about people to suggest the SU(3) theory [2] [3] and then the SU(6) theory[4,5], these theories have had good success. These convince people to think that the so-called existing elementary particles may not be the most fundamental particles, they themselves have some structure and can be decomposed. Gell-Mann suggested a model, according to it all the observed particles are made up of three more fundamental fermions called quarks. The surprised things are that these particles possess fractional charge and in particular the baryon wave function of 56 dimensional representation of SU(6) is completely symmetric which is not allowed by fermi statistics. People try in vain to find out these particles on high energy accelerators [7], it was supposed that their masses should be higher than tens of Gev [8]. However the mass of their bound state becomes very small, so it is inferred that the interaction between them will be very very strong beyond any we known, we may call it the super-strong interaction. The characteristics of the interaction demonstrate that the strongest coupling appears between particle and antiparticle or among three particles and brings about the formation of bound states whereas this super-strong interaction disappears between bound states. In this paper a model is proposed to try to obtain a unified understanding of the features mentioned above. As all of us accepted, the medium which transfers the electromagnetic interaction is the electromagnetic field, the charged particle interacts

* Translated from Chinese in ATOMIC ENERGY, No.3, 232 (1966)

with electromagnetic feild through its charge. By the intermediate vector boson theory, the medium which transfers the weak interation is the intermediate vector boson, particles which have weak interaction interact with intermediate boson field through their "weak charge". Similarly, we suppose that the medium which transfers super--strong interaction between quarks is scalar or vector field, quarks itself has certain "charge" Z . Quarks belonging to one class have the same quantum number z. It is easy to see that in order to overcome the difficult of statistics, we have to introduce at least three classes of quarks with different quantum numbers. We denote their quantum numbers by z_1, z_2, z_3. Each class involves three quarks, altogether we have nine quarks. Below, by the assumption of three classes of quarks described by new quantum number z. We will discuss the bound states and the interaction between bound states. Finally we brief how to test this theory.

II. THE SUGGESTION OF NEW QUANTUM NUMBER

The obseved hadrons satisfy Gell-Mann-Nishijima empirical formula

$$Q=I_3+Y/2 \ , \qquad Y=N+S \ , \tag{1}$$

where Q, I_3, Y, N, S are charge, third component of isotopic spin , baryon nmber, hyporcharge and strangeness of a particle. For quarks no immediate experimental confirmation exists for (1), we suppose that it should be changed to

$$Q=I_3+X/2 \ , \qquad X=Y+Z \ , \tag{2}$$

where Q, I_3, Y are the same as in (1), the additional Z is the new quantum number and it is invariant under SU(3) and SU(6), different eigen value corresponds different class of quarks .

As mentioned above, we suppose that three classes of quarks have different quantum numbers z_1, z_2 , z_3. Each one of the three classes belongs to the fundamental representation of SU(3) or SU(6). Quarks can constitute various representation of SU(6) without violation of fermi statistics, these quarks can constitute 56 dimensional representation provided they belong to different classes. Therefore below we will not discuss the symmetric problem of wave function again. Boson is the bound state made up of quark and antiquark, so

$$6 \otimes 6^* = 35 \oplus 1,$$

35 multiplet state is well-known and the singlet state may correspond to the experimental 959Mev resonance state X^0 [1]. Let 6_1, 6_2, 6_3 represent three kinds of quarks, then we have nine patterns of bosons, however in order to obtain the correct observed chage and hyperchrge of the boson, only three of them are possible, i.e.,

$$6_i \otimes 6_i^* = 35_i \oplus 1_i, \qquad i=1,2,3 . \tag{3}$$

An interesting question is which one of the three represents the observed boson, but up to now we have no answer. Probably the observed meson is their linear combination, for example,

$$35 = 1 / \sqrt{3}\ (35_1 + 35_2 + 35_3), \tag{4}$$

$$1 = 1/\sqrt{3}\ (1_1 + 1_2 + 1_3) . \tag{5}$$

Similarly, the 56 dimensional representation of three quarks of baryon comes from

$$6_1 \otimes 6_2 \otimes 6_3 = 70 \oplus 70 \oplus 56 \oplus 20 , \tag{6}$$

and in order to assure to give the correct experimental observed quantities of the 56 dimensional prepresentation, three classes of quarks must satisfy

$$z_1 + z_2 + z_3 = 0, \tag{7}$$

$$N_1 + N_2 + N_3 = 1, \tag{8}$$

where N_1, N_2, N_3 represent the baryon numbers of three kinds of quarks respectively. The question is : the multiplets of 70 and 20 are also observable, but why 56 multiplet is the lowest one in energy. In addition by the antisymmetric consideration, the 20 multiplet made up of one kind of quarks is also allowed, because its SU(6) wave function is completely antisymmetric. These problems will be discussed in the next section.

III. THE PROBLEM OF BOUND STATE

We suppose that there are three kinds of quarks, their quantum numbers satisfy (7) and (8). If we consider the observed mass spectroscopy of the elementery particles , the questions, we must ask, are why the bound state of quark and antiquark or three quarks have the largest binding energy, why the 35 and 56 multiplets are the lowest bound state and why the super-strong interaction disappears among the 35 and 56 multiplets. We do not know the answer, because at present there is not a available theoritical method to deal with the bound state of strong coupling, at the same time there is not a dynamics for quarks. In this case we try to make some explorations to understand the nature uncovered by experiments by only a simple method. In field theory it was known that under the non-relativastic limit the potential between two particles interacting through either scalar or vector feild will include a spin-independent term and a spin-spin term. Generally the spin-independent term is the most important one. Since in the bound state the velocity of quark is very smaller than light as pointed by reference

[8]. So we can make approximate treatment by non-relativistic mechanics. We suppose the interaction Hamiltonian between quarks to be

$$H_1 = \sum_{j\neq k} Z_j Z_k V(r_{j,k}), \tag{9}$$

where Z_j, Z_k are the Z operator acting on j, k quark respectively, $r_{j,k}$ is the distance between quark j and k. obviously this interaction is SU(6) invariance. Again we suppose that the interaction between quark and antiquark is also described by (9) . If all the particles are in the S state, the binding energy can be calculated by quantum mechanics. Ignoring the kinetic energy, the binding energy of meson described by (4) is

$$E_{35} = \langle 35|H_1|35\rangle = -1/3(z_1^2+z_2^2+z_3^2)\langle 35|V(r_{12})|35\rangle. \tag{10}$$

The binding energy of baryon is

$$E_{56} = \langle 56|H_1|56\rangle = (z_1z_2+z_1z_3+z_2z_3)\langle 56|V(r_{12})|56\rangle$$

$$= -1/2(z_1^2+z_2^2+z_3^2)\langle 56|V(r_{12})|56\rangle, \tag{11}$$

where $\langle 35|V(r_{12})|35\rangle$ and $\langle 56|V(r_{12})|56\rangle$ denote the average values of V of the wave function of one pair of particles in 35 and 56 multiplets respectively. It is worth to point out that if the quark wave function of the meson approaches that of the baryon, then

$$\langle 35|V(r_{12})|35\rangle \simeq \langle 56|V(r_{12})|56\rangle \tag{12}$$

$$E_{35}/E_{56} \simeq 2/3 . \tag{13}$$

This result can be understood as : for heavy quarks, the energy of bound state approaches zero by strong interaction, so the binding energy equals the rest masses of quaks approximately, that is

$$E_{35}/E_{56} \simeq 2M/3M = 2/3, \tag{14}$$

where M is the rest mass of quark.

If the meson are the bound state described by (3), (10) should be changed to $E_{35i} = -z_i^2 \langle 35_i|V(r_{12})|35_i\rangle$ and one has to postulate that the quark mass should be proportitional to its Z charge square. According to renormalization theory it means that originally the quark has no or very small mass, the observed mass comes essentially from renormalization effect. After appropriate modification, (10) is still meaningful. For simplicity below we will discuss the meson discribed by(4) only.

In the following we will talk about why there are only bound states of quark and antiquark or three quarks. For one quark state, in principle the interaction which violates Z conservation is possible and owing to the integer charge and large mass the free quark is unstable. For the meson of $6_i * 6_j^*$ $(i\neq j)$ bound state, the binding energy is proportional to $-z_i z_j = 1/2(z_i^2+z_j^2-z_k^2)$ $(i\neq j\neq k)$, by the postulation that the quark mass is proportional the Z charge square its energy is higher than that of the mesons described by (3) and (4), so it can be observed only at higher excited state. For the state of two quarks $6_i * 6_j$, its binding energy is proportional to $z_i z_j$,

$$z_i z_j = \begin{cases} z_i^2 & i=j; \\ 1/2(z_k^2 - z_i^2 - z_j^2) & i\neq j\neq k. \end{cases} \tag{15}$$

The first line means the interaction is repulsion, the second line means its energy level is very high. Similarly the binding energy of three quarks is proportional to $z_i z_j + z_i z_k + z_j z_k$,

$$z_i z_j + z_i z_k + z_j z_k = \begin{cases} -1/2(z_1^2 + z_2^2 + z_3^2), & i\neq j\neq k; \\ z_k^2 - z_i^2, & i=j\neq k, \\ 3z_i^2, & i=j=k. \end{cases} \tag{16}$$

The third line of (16) means it is a repulsion . The second line means that its energy level is very high if one postulates that the quark mass is proportional to its Z charge square. The first line means that only the bound state of three quarks belonging to different kinds is the lowest energy state.

So far we have explained why the observed elementary particless are the bound state of quark-antiquark and three quarks. Below we will discuss the situation when the quark number is increased. As mentioned above, all the observed bound state are zero eigen state of Z, i.e. "neutral" state, there is no interaction among them. Also the bound states are neutral locally, therefore there is no interaction even between bound state and an individual quark. All of these means that when one put more quark into a bound state only if the additional quarks is one of these bound state its energy can be the lowest one. Then we can understand why all the observed elementary particles are in pair of quark-antiquark or integer times of three. Except the interaction mentioned above, there is another possible SU(6) invariant interaction,

$$H_1' = \sum_{j \neq k} B_\mu^\nu (j) B_\nu^\mu (k) f(r_{j,k}), \tag{17}$$

where B_μ^ν is the SU(6) infinitesimal operator, $f(r_{j,k}) < 0$ is the function of the distance between j and k quarks. The average value of H_1' can be calculated in the similar way,

$$\begin{aligned} &\langle 35|H_1'|35\rangle - \langle 1|H_1'|\rangle = 12\langle 35|f(r_{12})|35\rangle < 0, \\ &\langle 56|H_1'|56\rangle - \langle 70|H_1'|70\rangle = 6\langle 56|f(r_{12})|56\rangle < 0, \\ &\langle 56|H_1'|56\rangle - \langle 20|H_1'|20\rangle = 12\langle 56|f(r_{12})|56\rangle < 0. \end{aligned} \tag{18}$$

Where we have postulated that the spatial wave functions of 35 and 1 multiplets as will as 56, 70 and 20 multiplets are the same,

$$\left.\begin{aligned} &\langle 35|f(r_{12})|35\rangle = \langle 1|f(r_{12})|1\rangle, \\ &\langle 56|f(r_{12})|56\rangle = \langle 70|f(r_{12})|70\rangle = \langle 20|f(r_{12})|20\rangle. \end{aligned}\right\} \tag{19}$$

Comparing with electromagnetic interaction, H_1' corresponds to the term of magnetic moment and we think it may be smaller than H_1. Although the energy level of singlet state is higher than 35 multiplet and the energy level of 70 and 20 multiplets are higher than 56 multiplet, they are still observable. However owing to the existence of interaction which violate the SU(6) invariance (it may have the same order as H_1') and owing to the orbit movement, all of these makes the distribution of higher excited states becomes very complicated.

IV. DISCUSSION

In this paper we postulate a possible model, some problems have not

yet been touched, but it is easy to show that the mass relation of SU(6), the relation of magnetic moment keep unchanged, in other word there is no difference between our model and the usual quark model. However the dificulties of the usual quark model, as the statistics, saturation of force, fractional charge, have been overcomed owing to the assumption of new quantum number. Of course these do not means that they can be considered as the proof of our model, many interesting problems have to be tested by experiments. In this respect one thinks at once to use the electromegnetic interaction, because quark possesses fractional charge in usual model, but in our model quark possesses integer charge. Neverthless not each process is model-dependent. For the electromagnetic decay of meson, as pointed in [8], only the process whith is related with the vertex of $\omega^0 \Rightarrow \gamma$ or $\phi^0 \Rightarrow \gamma$ can distinguish whether the particle charge is integer or not, these processes include $\pi^0 \Rightarrow 2\gamma$, $\pi^0 \Rightarrow e^+ + e^-$, $\eta \Rightarrow 2\gamma$ etc.. If one want to treat with these processes serioulу, one meets two problems, firstly the experimental accuracy should be improved (up to now the lifetime of η has not been determined). Secondly because it is a complicated theoritical problem of strong coupling bound state, the calculation of lifetime or branch ratio can be done only by making necessary approximate assumptions which turns the theoritical prediction into indefinite , so it is needed to investigate in future. There are also other possibilities to test this model, and the most direct one, of course, is to produce quark and to check if its charge is integer or not and if there is a quantum number Z or not.

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