A Systematics and Phenomenology of Hadrons*

Jugoro IIZUKA,** Shoichi HORI,*** Ken-ichi MATUMOTO,***
Eiji YAMADA*** and Masatoshi YAMAZAKI***

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The hadron structures, levels and their mutual interactions are discussed based on the combined scheme of the composite model, U (3) symmetry and the non-relativistic inner dynamics. In particular, the hadrons with the lowest triplet configuration (meson with $(t\bar{t})$- and baryon with (ttt)-structures) are investigated and compared with the available data. Futhermore the proposed urbaryon models are examined in connection with our studies on hadrons.

§ 1. Introduction

The experiments in these ten years have shown the existence of many resonance states for mesons and baryons with various spin, parity, isospin and hypercharge values. Indeed there exist too many varieties of resonance states to be considered as fundamental entities by any possibility. Bisides the number of them is now being on the steady increase. On the other hand we have no established theory to account for them. In such a situation, we believe that every possible way of approach should be tried even if it may not be with the consensus of most of physicists.

A considerable progress in hadron physics has been made along the line suggested by Sakata's composite model[1]. The natural conclusions deduced from the idea developed by Sakata and his School are*):

1) The prediction of the existence of a large variety of hadron resonances.
2) The classification in terms of U(3) symmetry[2].
3) Mass formula approach for hadrons and a nonrelativistic picture of hadrons based on definite configuration[3].
4) Field theoretical approach for composite systems[4].

The first three points were already reported by Ohnuki[5] at the 10th Rochester Conference (1960).

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** *Department of Physics*
****Department of Physics, Faculty of Science.*

*) The detailed arguments on these points can be found in the papers contained in Supple. of Prog. Theor. Phys., 19 (1961).

These kind of investigations were performed in the early stage of Sakata model. The huge accumulation of experimental data thereafer has indicated the necessity of a certain modification of the original model which treated p, n and Λ as fundamental particles. Among the various modifications proposed by many authors, the Eightfold Way by Gell-Mann[6], Ne'eman[7] and Okubo[8], and the quark-ace model*) by Gell-Mann[9] and Zweig[10] were the most successful and the most promising developments.

The quark model has succeeded in clarifying most of symmetrical properties of hadrons. The penetration to the dynamical problems of hadrons was brought by the proposal of SU(6) symmetry by Gürsey-Radicati[11] and Sakita[12]. Since the introduction of the SU(6) symmetry, many attempts have been made to boost the SU(6) group and to make the theory relativistic. It seems doubtful, however, whether these attempts were quite successful, especially when the boosted symme tries are taken into the formalism of the second quantized field. We believe that the success of SU(6) symmetry suggests the nonrelativistic character of dynamics governing the internal structure of hadrons as discussed by Ohnuki-Toyoda[13], Nambu[14] and Moropurgo[15]. Remarkable successes of the calculations on the structure of hadrons by many authors[16] based on the nonrelativistic dynamics may be taken as supports for the standpoint. Of course, no one knows whether the internal dynamics is actually nonrelativistic or not. It is an open question which should be clarified in future.

In this work we assume the above stated standpoint, and reexamine the old idea under the new situation in the light of so far accumulated experimental data. Our fundamental assumption is that a hadron is a nonrelativistic bound state of more fundamental particles-triplet urbaryons and/or anti-urbaryons. The success of SU(6) symmetry indicates that the forces acting between urbaryons and/or anti-urbaryons are mainly spin and unitary spin independent. From this standpoint, SU(6) symmetry can be regarded as a kind of dynamical symmetry which is valid only for S-states.

The primary forces between urbaryons and/or anti-urbaryons may be considered to be mediated by a heavy vector boson as suggested by Fujii[4]. Closer investigations reveal, however, that the shape of the potential must be similar to that of square well rather than that of Yukawa potential. The nonrelativistic approximation does hold if $\mu^2/M^2 \ll 1$, where M is the mass of the urbaryon and μ^{-1} is the range of the potential**. We confirmed that the lower energy levels of a Dirac particle bound in a square well potential are approximately equal to those of a particle obeying the nonrelativistic Schrödinger equation up to the order

*) We feel that it is more appropriate to use the name quark-ace or ace-quark but We use the name quark hereafter for brevity.

**) If the potential were of Yukawa type, the motion of the particle would be highly relativistic even if the above conditions were satisfied.

indicated above. The approximate equality holds even in the limit where the binding energy is twice of the mass of the particle and the depth of the potential is twice of the mass plus kinetic energy, beyond which the one-body treatment is no more valid.

We assume that the primary force is the one derived from the broad square well potential which almost cancels the masses of constituent urbaryons and/or anti-urbaryons[17]. In this model, the mass differences between the composite systems are mainly attributed to the kinetic energy differences of the system. The energy levels of the system will be further split due to symmetry breaking interactions (S. B. I.), spin-orbit couplings, spin-spin interactions and so on, all of them being treated as perturbations. Since our primary force is spin and unitary spin independent and does not contain pair effects, the whole system is symmetric under $U_t(3)\otimes U_{\bar{t}}(3)$ group. The perturbation by the pair effects will reduce the symmetry to that of U(3) group. The final level pattern for mesons will be determined through the competition between symmetry breaking interactions and pair effects.

The results on the meson mass levels and the related topics is reported in §2, where some kind of dependence of the forces between two urbaryons (anti-urbaryons) will be allowed. We show that the observed mesons can be well described by the $(3,3^*)_a$ -series. Similar considerations is applied to baryon levels in §3. Low lying baryon states are assumed to be nonrelativistic bound states of three urbaryons. The important problem in the case of three body system is the choice of position variables. It seems to us that the variables employed by Blatt-Derrick[18] in the treatment of triton and He^3 are the most convenient ones for symmetry consideration. With this choice of the symmetric position variables it is shown that the unitary octets are neccessarily the intrinsic spin doublets and the unitary spin decuplets and singlets are the intrinsic spin quartets at least for low lying levels. The results of our tentative evaluation are compared with experimental data. Other possible models are also briefly mentioned.

In §4, we discuss a possible operative form of hadron interactions, which follow as a rather natural consequence of the nonrelativistic picture (N. R. P.) assumed in this report. There the selection principle is introduced to obtain and also to understand the dominant characteristics of hadron interactions. The brief comparison of the models which were proposed as the modifications of the quark model is made in §5. The three triplets model is discussed in some detail as one of the promising model.

§ 2. The meson mass levels and the related topics

As the first stage, we classify the hadrons in terms of the $U_t(3)\otimes U_{\bar{t}}(3)$-configurations with definitte n_t and $n_{\bar{t}}$, spin, parity and other possible quantum numbers. We may describe the situation as follows:

$$
\begin{array}{ll}
\text{mesons} & \left\{ \begin{array}{l} (3_p,\ 3^*)_A \quad (3_p,\ 6)_A \quad (6_q,\ 6^*)_A \\ (3^*_q,\ 6^*)_A \quad (8_r,\ 1)_A \quad (8_r,\ 8)_A, \quad \text{etc.,} \\ n_t = 3p+1,\ 3q-1 \text{ or } 3r \end{array} \right. \\
(n_t = n_{\bar{t}}) &
\end{array}
\qquad (1)
$$

and similarly for baryons with $n_t - n_{\bar{t}} = 3$,

where A denotes the total angular momentum, parity and some other quantum numbers of the relevant system. We may admit a possible presence of certain new matter in habrons, though we concentrate our discussions to the fermion triplet involved. It should be noted that only the configurations given in the above are stable in the models, which will be discussed in §5. It is quite reasonable, however, to expect from the past experience on particle physics, that the existence of the mesons with higher configurations strongly depends upon the properties of inner urbaryon dynamics. For example, if the primary forces between $(t\,\bar{t})$-and $(t\,t)$-pairs are similar, in characteristics, to the electromagnetic one[17)19)20)], the effective supercharge of t and so the effective two-body forces will be reduced to a certain extent. This reduces, in turn, the degree of cancellation of the urbaryon rest masses by the forces. This observation together with the non-zero kinetic energy contributions may lead us to expect that the mesons with higher configurations would appear in higher excited states, if the forces were of the above assumed character.

As the next stage, the degeneracies of the above multiplets are removed by the introduction of the pair effects and the U(3)-symmetry breaking interactions (S. B. I.). We consider the lowest order contribution of the pair effects to the mass shifts, i. e.,

$$\delta m_p \text{ due to pair effects} \sim 1 \text{ of } (9,\ 9) \sim \rightleftarrows \otimes \otimes \rightleftarrows, \qquad (2)$$

where $\otimes$ denotes the single pair creation or annihilation vertex. As for S. B. I., we follow the work of Ishida[16)] and Zweig[10)], i. e.,

$$\delta m_s \text{ due to S. B. I.} \sim T^3_3 \text{ of } (9,\ 1) \oplus (1,\ 9). \qquad (3)$$

The spin independent character of S. B. I. effects is quite obvious by assumption[10)16)]. We also note that its magnitude is likely of the order of the μ-meson mass, a value conjectured long before by Sakata and his school[21)].

In next and further stages, we must consider various hyperfine effects neglected so far such as the effects of spin- and unitary spin-dependent forces, the non-linear S. B. I., the multi-pair or the hadron cloud effects, the recoil effects and their correlations, etc.. It is easily conceivable that these effects would become more and more important in higher excied systems with multi-particle configurations, in particular for the systems with hadron clusters. The subjects of these stages will be left untouched in our studies, since they are likely beyond the frame work of N. R. P. The classification of the available meson levels to date was made by one of us[22)] and by Dalitz[23)]. Leaving their details to the quoted

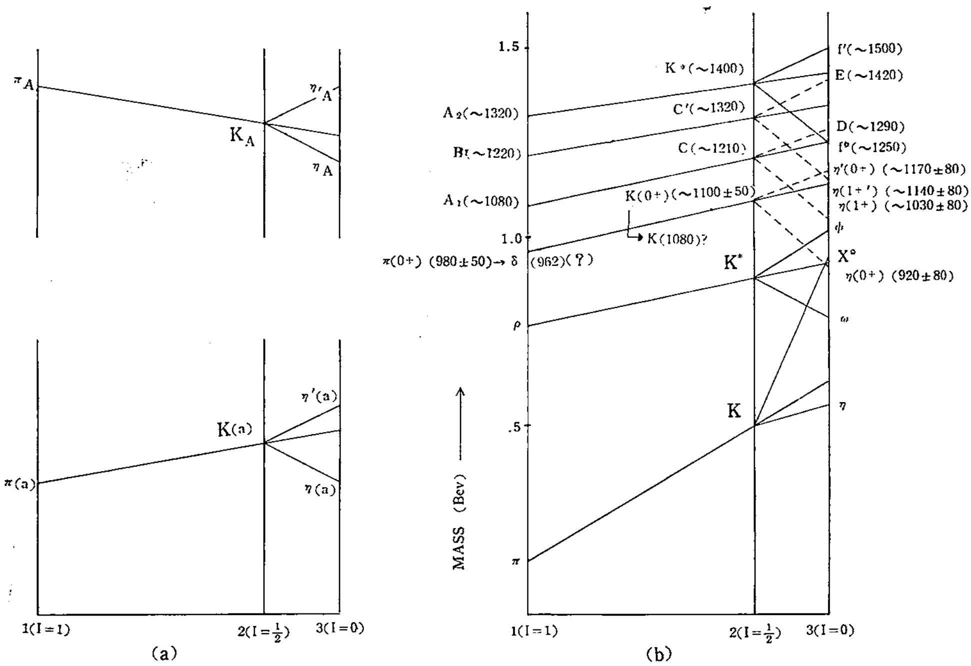


Fig. 1 : Graphical representations of the octet or the nonet states. These states, following the GMO formula, are represented by the intersections of 1(I=1), 2 (I=1/2) and 3 (I=0) axes with appropriate straight lines. Note K–π: X_8–π=3 : 4, where π, K and X_8 denote I=1, 1/2 and 0 states with arbitrary spin and parity. (a) shows the ideal case, $\delta m_p=0$ and $\delta m_s \sim$ 100Mev. (b) shows the classifications of the observed levels together with the predicted ones. The lower pattern is the Ishida-Zweig one. while the upper one is the inverted type.

papers, we give Fig. 1 and the two points. i) The dominant configuration of these classified mesons are all of the type*)[24] $(3_0, 3^*)_a$, $a=(n=1, {}^SL_J)$ and n denotes the principal quantum number. ii) Except ${}^1S_0-9$, which will be discussed later, δm_p is less than or of the order of 70Mev for $L\leqslant 1$. As for i), we may repeat Dalitz's argument[23], i. e., it is quite difficult from our standpoint to assume that the meson levels used in our classification such as $2^+-9(A_2$, K^*, f′ and f°) have some four body configurations. This is partly because the expectation remarked before on meson levels with higher configurations and partly because there is no reasonable possibility to predict or reproduce the observed level patterns and the decay properties. In fact, possible candidates of the nonet mesons with $n_t=n_{\bar{t}}=2$ are limited to either $(3_1^*, 3)_A$ or the member of $(6_1, 6^*)_A$, i. e., $T^{[\alpha\beta]}_{[ij]}$ or $T^{(\alpha\beta)}_{(ij)}$ with $n_t=n_{\bar{t}}=2$ in tensor notations. As is easily seen, our scheme predicts that $(3_1^*, 3)_A$ has the inverted Ishida-Zweig pattern (I. Z. -pattern) and it has a quite different decay property from, say 2^+–9 observed, as will be discussed in §4. In the second case, the nonet structure requires that the $1-8$ mass

*) In the following, the subscript 0 will be dropped.

shift δm_p (1−8) in the reduction $(6_1, 6_*)_A \to 1+8+27$ due to the pair effects must be reasonably small, which in turn means 27 to be in close to 8. Indeed we have, from Eq. (2):

$$m(8) - m(1) : m(27) - m(8) = 3:5. \quad (4)$$

Thus 27 cannot be separated far apart from 8, since $\delta m_p \lesssim 70$Mev for 2^+-9 as is seen from A_2-f°. Furthermore S. B. I., Eq. (3), introduces the strong mixings among 27−8 and 8−1. With $\delta m_p \lesssim 70$Mev, two $I=\frac{1}{2}$, one $I=0$ and three $I=1$, two $I=\frac{1}{2}$ and $\frac{3}{2}$, and finally one set of I=0, 1, 2 mesons will respectively lie in nearly degenerate levels. For $\delta m_p(1-8) \gtrsim 100$ Mev, the level patterns as well as the decay properties are considerably modified compared to $\delta m_p \lesssim 70$Mev. Summarizing the above considerations together with the nearly satisfied equidistant relations predicted by the LS- force ($L=1$ system), we may conclude that the classified mesons have $(3, 3^*)_a$ as their dominant configuration.

Let us discuss the ${}^1S_0-9$ irregular patterns. We understand that this is the manifestation of certain unusually complicated dynamics in the innermost region, say $r \lesssim \frac{1}{M_t}(1\sim 2)$ where M_t is the urbaryon mass and so it is quite beyond our simple dynamical consideration. In our studies, we totally adopt the existing data on ${}^1S_0-9$ as the phenomenological input. We remark however that the parameters such as δm_p, δm_s and the strength of the spin-spin force determinrd from ${}^1S_0-9$ (and using ${}^3S_1-9$ for the last example) may not be taken as the common and good measures of those appearing in the subsequent higher levels. This kind of approach is well-known as the Taketani approach[25] in the nuclear force problem. From this approach, we expect that the level patterns of the meson series $(3,3^*)_a$ are directly connected with the dynamical characteristics of the relevant force region. A possible application of this approach is shown in Table 1.

Table 1. A possible application of the Taketani approach to the $(t\,\bar{t})$-dynamics. We consider that the mass level patterns of meson nonet series directly reflect the dynamical characteristics of the classified regions.

Regions	Characteristics
Innermost region $r \lesssim (1\sim 2)\frac{1}{M_t}(=r_t)$	Multi-pair effects, S.B.I., dipole-dipole int., and their correlations, something unknown. ...
Intermediate region $r_t < r < 1$ Bev^{-1}	V_P, LS, other minor forces (spin dependent, tensor, quadratic LS,... with appropriate U(3)-character)
Hadron region 1 Bev$^{-1} \gtrsim r$	tail of V_P, LS, forces due to hadron exchanges, ...

We close the discussions on this topic with a comment on δm_s. Its origin may be either Nagoya model[21] like or due to the vector meson[26] coupled to t_3 or the hypercharge. In the latter, the marked differences betweeu ${}^1S_0$- and ${}^3S_1$-,

${}^{\iota}P_J$–9 and also the nearly satisfied linear patterns in the baryon–$8\oplus10$ show that the relevant meson cannot be identified with the existing low-lying ones such as ω and ϕ. In fact, it must be quite massive, say $m_v \gtrsim \frac{1}{2} M_t$, where $M_t \gtrsim 4.5$Bev[22] and $M_t \sim 10$Bev is conjectured by several authors[14)27)].

§ 3. Baryon mass Levels

In the present section we assume that the potential between two urbaryons is the attractive square well potential with the depth $V_0 \approx M_t$ and the width ≈ 1 Bev^{-1}. The relation of this potential to the urbaryon-anti-urbaryon potential which is responsible for meson mass levels will be the main subject of the subsequent section. After Derrick[18] we choose as the position variables the three sides r_{23}, r_{31}, r_{12} of the triangle made by three urbaryons and the Euler angles α, β, γ which describe the space rotation of the triangle, besides the centre of mass coordinates $\boldsymbol{r}_G$. Schrödinger equation written in terms of these variables was given by Derrick[18]. The kinetic energy consists of three terms: the vibrational and rotational energies and the coupling energy between them. The spin-orbit coupling will be treated as a small perturbation.

We assume that the over all wave function is always symmetric under the permutation of three particles. It is the product of the internal (or vibrational) wave function $f(r_{23}, r_{31}, r_{12})$, the Euler angle wave function and the spin-unitary spin wave function. We may confine ourselves to the case of a symmetric internal wave function for the discussion of low lying mass levels, because wave functions with the other symmetry properties correspond to higher mass levels. The Euler angle eigenfunction for orbital angular momentum L, z-component thereof M, and body-z-component μ is given by

$$D^L_{\mu M}(\alpha, \beta, \gamma) = \frac{i^{M-\mu}}{(M-\mu)!}\sqrt{\frac{(L+M)!\ (L-\mu)!}{(L-M)!\ (L+\mu)!}}\left(\sin\frac{\beta}{2}\right)^{M-\mu}\left(\cos\frac{\beta}{2}\right)^{-M-\mu}$$
$$\times G_{L+\mu}\left(1-2\mu,\ 1+M-\mu;\ \sin^2\frac{\beta}{2}\right)e^{i\mu\alpha+iM\gamma}, \qquad (5)$$

where $G_n(a, b; x)$ is the Jacobi polynomial of degree n. We choose as the body-z axis the normal to the plane determined by three particles and the body-x and body-y axes to be the principal axes of the moment of inertia of the triangle made by three particles. The eigenfunction $D^L_{\mu M}(\alpha, \beta, \gamma)$ together with $D^L_{-\mu M}(\alpha, \beta, \gamma)$ forms the basis of four irreducible representations of dihedral group D_2 and the space reflection P and the permutation P_{ij} of any two of three particles correspond to umklappen (half turn) operations U^z and U^x about the body-z and body-x axes, respectively. Therefore we get

$$PD^L_{\mu M} = (-1)^{\mu} D^L_{\mu M} \qquad (6)$$

$$P_{ij}D^L_{\mu M} = (-1)^{L} D^L_{-\mu M} \qquad (7)$$

Instead of $D_{\mu M}^{L}$, we define the normalized Euler angle wave function $Y_L^M(P_e, |\mu|)$ as follows,

$$Y_L^M(P_e, |\mu|) = \left[(2(2L+1))^{\frac{1}{2}}/4\pi\right] D_{\mu M}^{L} \qquad (8)$$

$$P_e = s \text{ for even } L$$
$$= a \text{ for odd } L$$

for $\mu = 0$ and

$$Y_L^M(s, |\mu|) = \left[(2L+1)^{\frac{1}{2}}/4\pi\right](D_{\mu M}^{L} + (-1)^L D_{-\mu M}^{L}) \qquad (9)$$

$$Y_L^M(a, |\mu|) = \left[(2L+1)^{\frac{1}{2}}/4\pi\right](D_{\mu M}^{L} - (-1)^L D_{-\mu M}^{L}) \qquad (10)$$

for $\mu \neq 0$, where $P_e = s$ or a denotes the permutation symmetry. It can be seen that the Euler angle wave function is always symmetric or anti-symmetric and never has the mixed symmetry. Consequently the spin-unitary spin wave functions are confined to the symmetric ($\underline{56}$) case and the anti-symmetric ($\underline{20}$) case. This means that the unitary octets are the intrinsic spin doublets and the unitary decuplets and singlets are the intrinsic spin quartets*).

We may consider that low lying states have a common (symmetric) internal wave function. Further it can be shown that the coupling energy between vibration and rotation is negligibly small in the present case. Therefore the mass difference between low lying states can be attributed mainly to the differences of the rotational kinetic energies. Thus we are naturally led to the problem of a spinning top.

(a) the symmetric top model[28].

The rotational kinetic energies for an oblate symmetric top with equilateral triangle configuration are

$$< 1/I_c > [L(L+1) - \frac{1}{2}\mu^2], \qquad (11)$$

where I_c is the moment of inertia about the body-z axis. We have always the relation,

$$E(L_{|\mu|}) > E(L_{|\mu|+1})$$

for this model. The result is illustrated in Fig. 2 with the appropriate LS splitting which will be stated below. Although we have shown that the mixed representations $\underline{70}$ and $\underline{70'}$ do not appear in lower mass region, still too many levels are predicted according to this model, compared with the observed levels. If the equilateral configuration would be the most stable one, this model would be a good approximation. In reality asymmetric configurations sometimes become more stable. This is a kind of Jahh-Teller effect[29].

(b) the asymmetric top model[30].

In this case we must take into account the internal degree of freedom ex-

*) This characteristics is different from the result obtained by Dalitz[23].

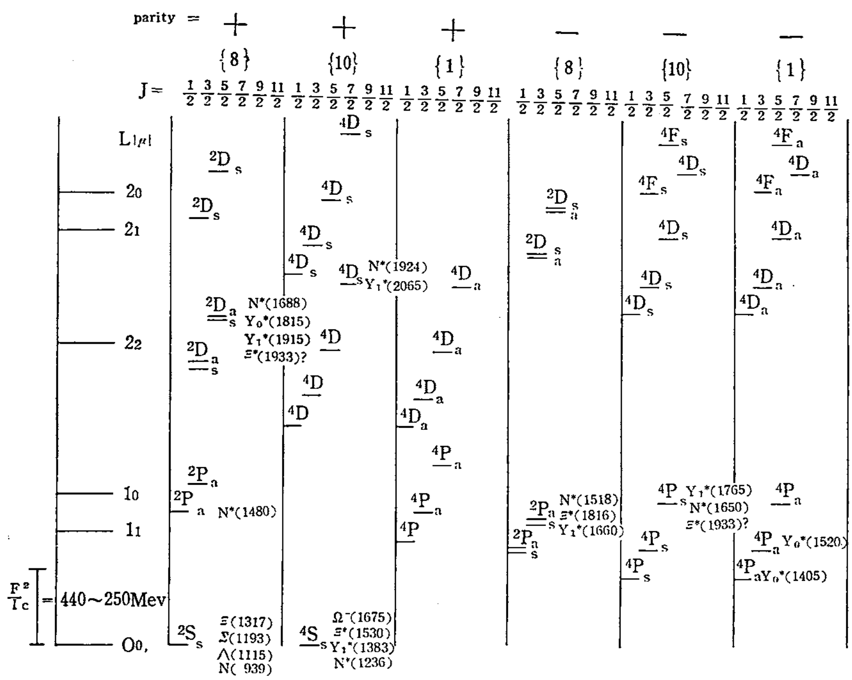


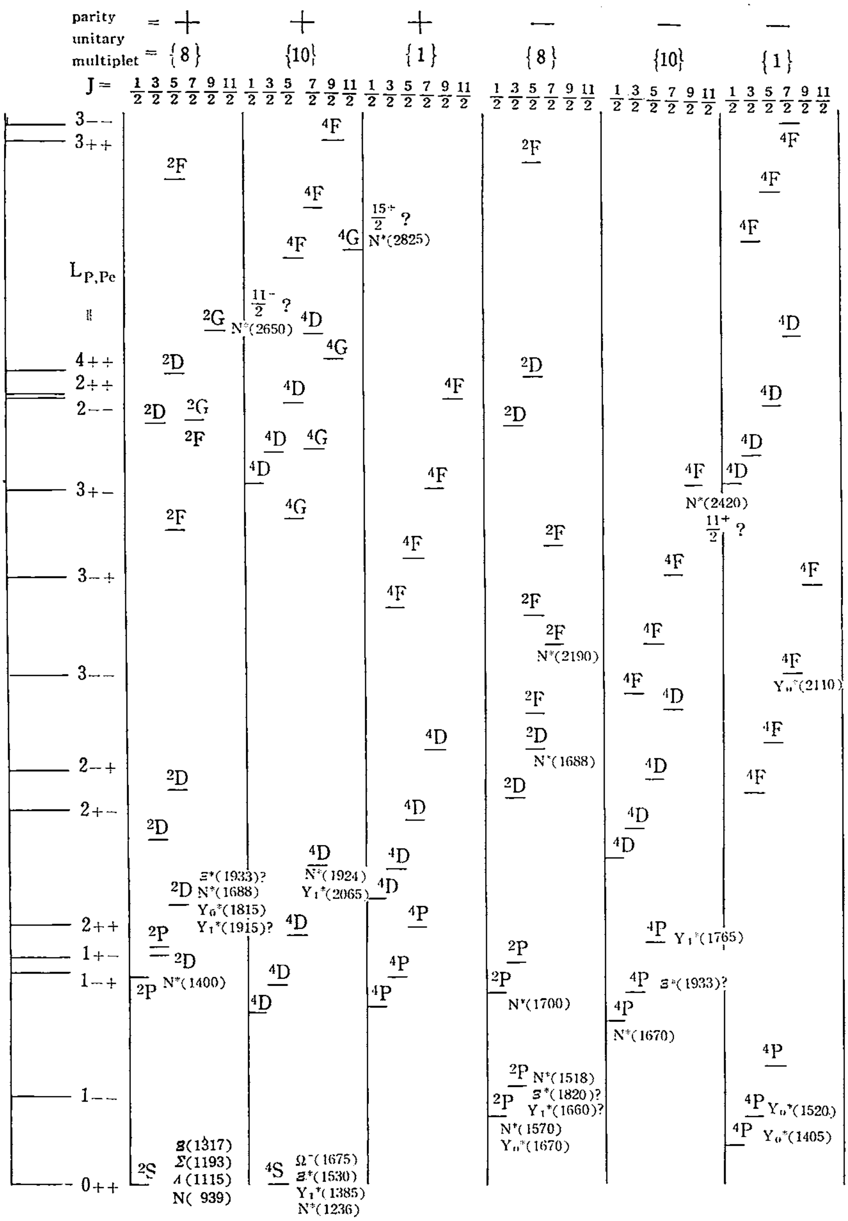
Fig. 2 : Baryon Mass Levels. Symmetric top model.

plicitly. Simultaneously we consider the effect of the repulsive core. As a crude approximation we assume that the probability amplitude is constant inside the potential well. Then the expectation values of the hamiltonian become equivalent to arithmetical averages of the rotational energies of asymmetric rotators apart from an additive constant, which have been computed by means of the Monte Carlo method. The results are plotted against the ratio y of the core radius to the range of the potential and compared with experimental data. Among the $2L+1$ levels with the angular mometum L, certain levels $L(P, P_e) = 0(+, s)$, $1(-, a)$, $2(+, s)$, $3(-, a)$, $4(+, s)$, ・・・ stay low lying but the others become highly excited, when the ratio y reduces.

(c) LS coupling

The matrix element of $\mathbf{L_{12}}\cdot(\mathbf{S_1}+\mathbf{S_2})$ has been evaluated according to the techniques of Racah. Then the expectation values with respect to the internal wave fucntion have been computed after the same method as stated above. The gross patterns thus obtained for low lying mass levels are illustrated in Fig. 3 i) ii) iii) corresponding to various choice of the core radius.

N*(1480) is hard to be reconciled with this scheme. Indeed its counter particles have never been observed. No unitary singlet with even parity has observed as yet. The fact is consistent with the present result. When the ratio y reduces, the $\frac{5}{2}^-$ -decuplet N*(1650) and Y_1^* (1765) becomes excited higher and higher. Reasonable result will be obtained around $y = 0.2$.



Eig. 3 : i) Baryon Mass Levels

The ratio of the core radius to the range of potential = 0.4

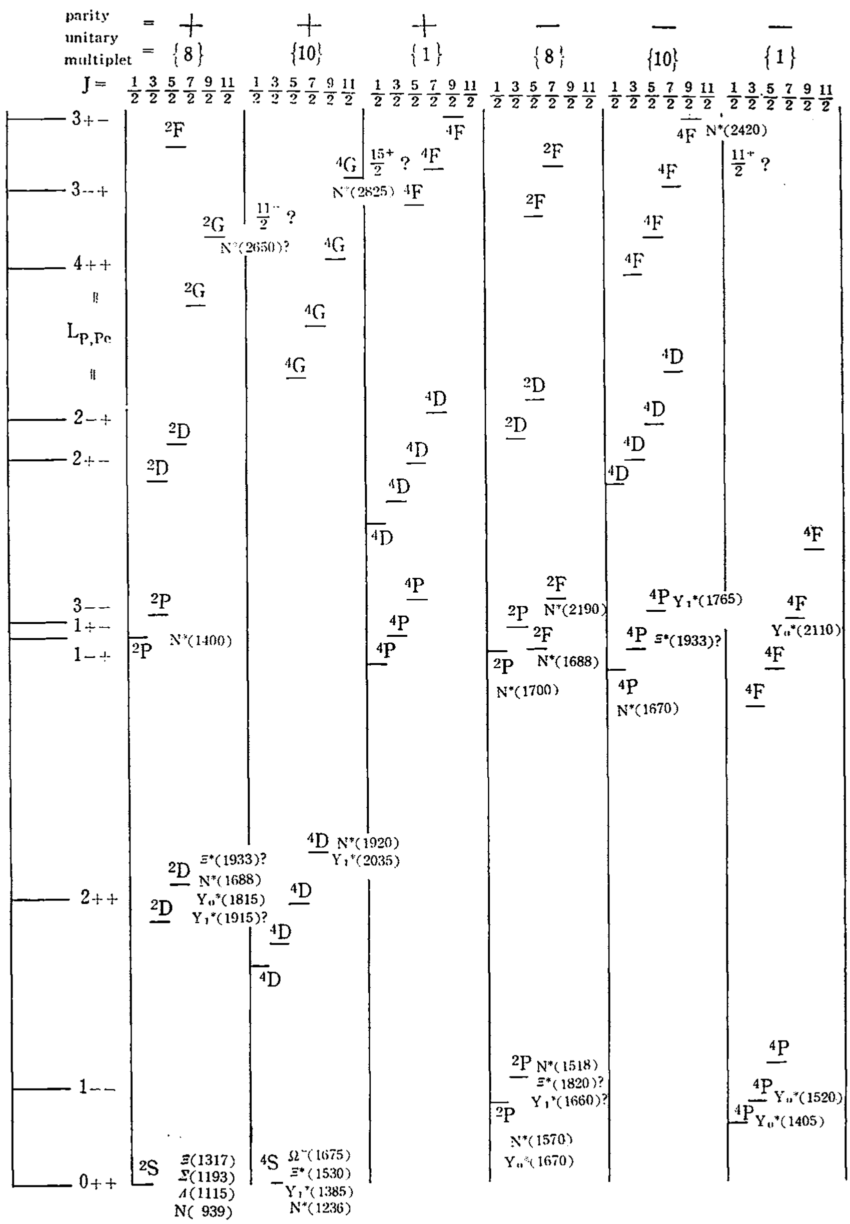


Fig. 3 : ii) Baryon Mass Levels

The ratio of the core radius to the range of potential = 0,2

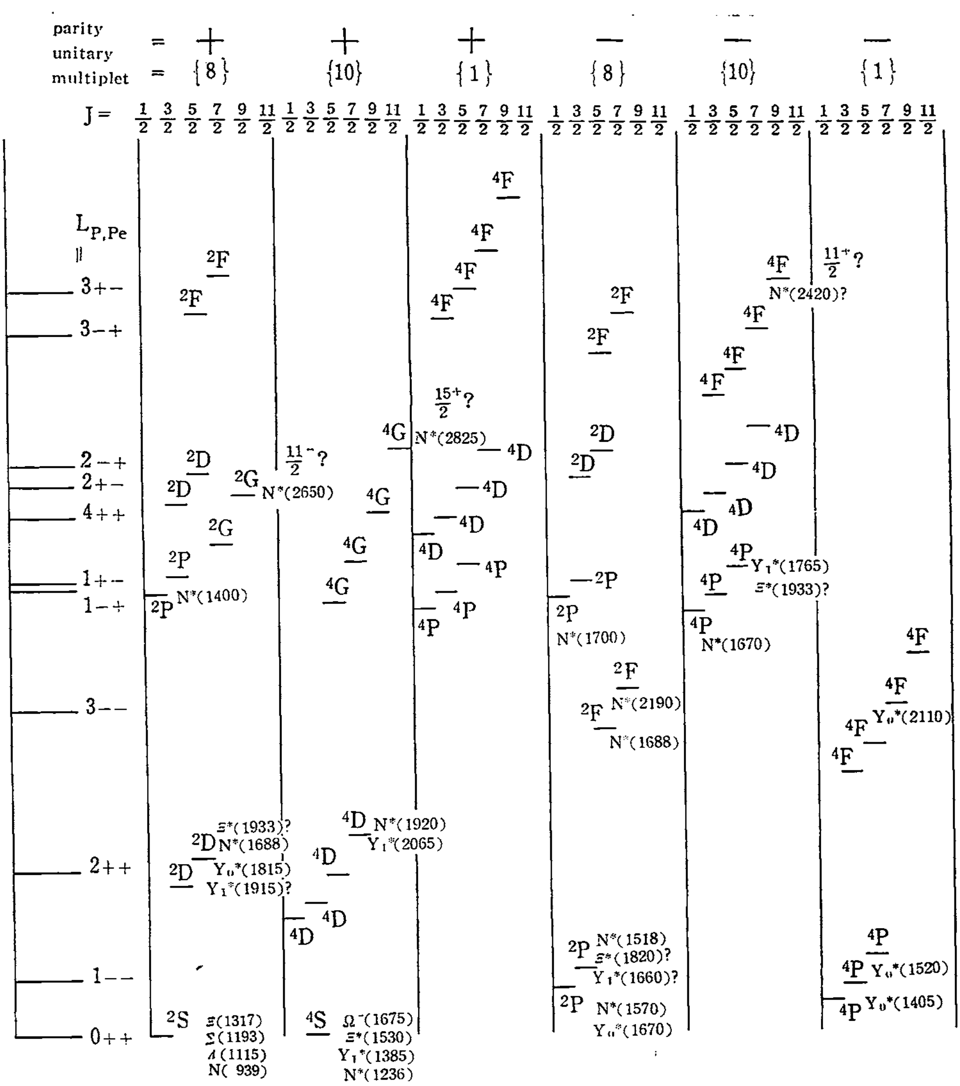


Fig. 3: iii) Baryon Mass Levels

The ratio of the core radius to the range of potential = 0.

Experimental data seem to reveal the following regularity similar to the Regge pattern,

$$8: \quad \frac{1}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+, \frac{7}{2}^-, \frac{9}{2}^+, \frac{11}{2}^-, \cdots$$

$$10: \quad \frac{3}{2}^+, \frac{5}{2}^-, \frac{7}{2}^+, \frac{9}{2}^-, \frac{11}{2}^+, \frac{13}{2}^-, \cdots$$

the regularity first suggested by Kycia-Riley[31] for $Y = 1$ baryons. One of possible ways to explain this regularity is to change the sign of the LS coupling term and to assume that only the states with the highest J are stable enough to be observed.

Another approach was made by Tati, Nagai and Okada[32]. They considered that three urbaryons move in a common effective potential well, and only one urbaryon is excited and the other two always remain in the ground state. They also assumed the spin-spin interaction $f\mathbf{S}_i \cdot \mathbf{S}_j$ where $f \approx 200\text{Mev}$ and the rule $J = L + S$ which corresponds to Kycia- Riley's rule[31] $J\text{-}L = I\text{-}l$ which was derived from the two-body N-π model. Based on these assumptions they could reproduce the above-mentioned regularity fairly well.

On the other hand Otsuki and Sawada[33] took the two-body N-π model (the molecular model) and assumed that the system is subjected to the Klein-Gordon equation with square well potential. By adjusting unitary spin dependent LS potentials suitably, they could explain the known data of nucleon levels.

§ 4. Strong interaction vertices and the selection principle

The extension[34] of N. R. P. to relatively simple phenomena on hadron interactions is unique and obvious in the sense that the dominant characteristics of a given process should be determined by the introduction of the minimum number of pair effects, which are generally required for the existence of the process.

Let us apply this idea to the effective vertices among hadrons. These vertices can be described by the number of pair vertex and the $U_t(3) \otimes U_{\bar{t}}(3)\_$ configurations of the participating hadrons, since the mass shifts due to pair effects are small and S. B. I. gives rise to no change on the separate conservation of n_t and $n_{\bar{t}}$. We remark at this stage that the following postulate is consistent with N. R. P.: among all of possible vertices of a given process (say $a \to b + c$) that respect the requirement of the minimum pair effects, the ones that again respect the minimum pair effects for any of possible restricted crossing processes (R. C. -processes such as $\bar{b} \to \bar{a} + c$, $c \to a + \bar{b}$, etc.) would controll the major part of the process. This princlple of selecting the dominant effective vertices (D. E. V.) out of many possible ones of a given process was called the "*selection principle*"[35]. We rephrase its content from the view point of the composite model diagram.

Selection principle (S. P.) :

Among all of possible effective vertices of a given set of hadrons, the dominant ones correspond to the connected diagrams viewed from the composite model.

We give their examples in Fig. s (4) and (5).

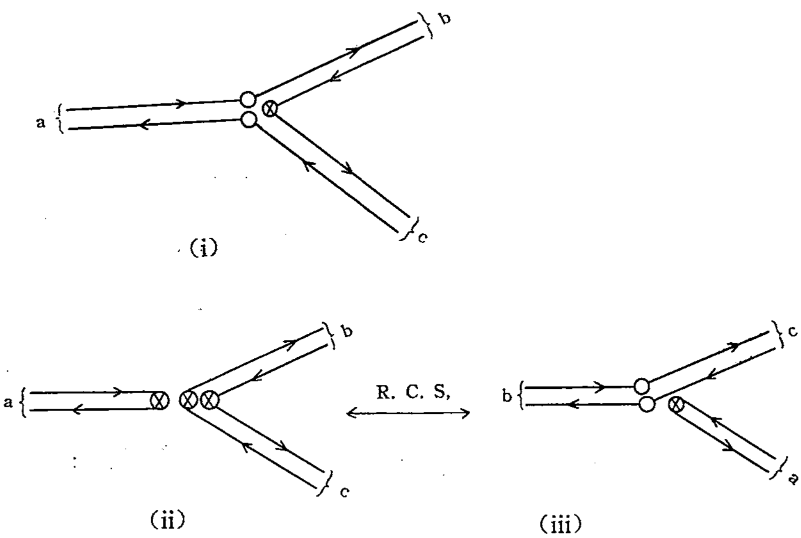


Fig. 4 : Composite model diagrams of the trilinear vertices of the meson nonets a, b and c. ⊗ denotes the pair effect, while ○ means the triplet or anti-triplet conserving part. (i) is the connected diagram, so it represents the dominant vertex made of a, b and c. (ii) and (iii) are the disconnected ones. These diagrams are transformed into each other under the restricted crossing symmetry.

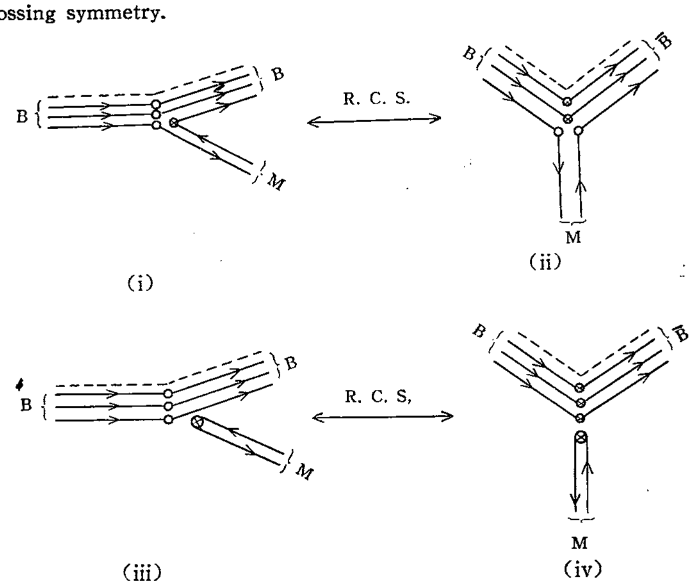


Fig. 5 : The diagrams of the meson-baryon vertices. The dot line indicates a possible existence of new matter in baryons. (i) and (ii) are the connected diagrams, while (iii) and (iv) are disconnected ones,

In other words, S. P. picks up those vertices that minimally violate the separate conservations of n_i and $n_{\bar{i}}$ (and so n_{t_i}, $n_{\bar{t}_i}$ assuming the appropriate fixing of U(3)-space) in any R. C.-reactions conceivable for a given set of hadrons. The following experimental facts may be taken as good evidences of S. P., if we assign appropriate configurations to the relevant hadrons: 1) The substantial abundance of $S=0$ meson generations over $S \neq 0$ pairs in $N\bar{N}$-annihilation processes[36]. The low rates of $N\bar{N} \to 2\pi$, $K\bar{K}$, etc, may also be taken as the evidence of the pair suppressions and S. P.. 2) The decay characterisitics of 1^-- and 2^+-9 and some other mesons[37]. 3) The quite low production rates of ϕ (and perhaps f′) over those of ω and f^0 in π N-collisions[38]. 4) Some features of the electromagnetic form factors of the nucleons[39], etc.

Leaving their details to the quoted paper again, we discuss the point 2) in connection with configurations. It is evident from our approach that the socalled Okubo's ansatz is included in S. P. by identifying the nonet mesons with $(3, 3^*)_a$ rather than with $(3^*_1, 3)_A$ or set of nine mesons in $(6_1, 6^*)_A$. In fact, D. E. V. of $(3^*_1, 3)_A$ and $(6_1, 6^*)_A \to (3, 3^*)_a + (3, 3^*)_b$ are, from S. P.:

$$
\begin{aligned}
H(T'_A \phi_a \phi_b) &= g\, T'_A{}^{[\alpha\ \beta]}_{[i\ j]}\, \phi^{\ i}_{a\alpha}\, \phi^{\ j}_{b\beta} \\
H(T_A \phi_a \phi_b) &= g'\, T_A{}^{(\alpha\ \beta)}_{(i\ j)}\, \phi^{\ i}_{a\alpha}\, \phi^{\ j}_{b\beta}
\end{aligned}
\tag{12}
$$

where g and g' denote the appropriate coupling strengths. From Eq.(12), we obtain the following decay properties of 2^+-9 with $(3^*_1, 3)_A$:

$$
\begin{aligned}
2^+ - \underline{9} &\not\longrightarrow 1^- - \underline{9} + 0^- - \underline{9}, \\
&\longleftrightarrow 2(0^- - \underline{9}),\ 2(1^- - \underline{9}).
\end{aligned}
$$

The same is true for the two sets of nine mesons in $(6_1, 6^*)_A$; $T^{(k\alpha)}_{(kj)}$ and $T^{(3\alpha)}_{(3j)}$, where the repeated index k denotes the sum over 1 and 2. These are in obvious disagreement with the observed data. One can obtain the consistent result making the requirement that the vertices with the double pair effects are dominant. In our picture, however, this requirement is certainly unacceptable. We simply note the two difficulties for these assignments. Firstly it is very difficult to suppress $0^- - \underline{9} + 0^- - \underline{9}$ mode and in fact it is far more worse than the case of $(3,3^*)_a$-assignment. The second difficulty is concerned with the level patterns (See § 2) and also the existence of $I = 2$, $\frac{3}{2}$ and 1 ($S=0$, ± 2) mesons around A_2, K^* and′ f' mass regions, respectively, for $2^+ - \underline{9} \equiv T^{(k\alpha)}_{(kj)}$. As for $2^+ - \underline{9} \equiv T^{(3\alpha)}_{(3j)}$ the similar meson levels will be in the lower mass region than $2^+ - \underline{9}$.

We add our expectation that the decay characteristics such as given in the above examples may be shown up in the higher excited systems with multi-particle configurations, an analogous phenomena to the fission-type processes in nuclear physics, this point being in fact the general content of S. P..

The following predictions resulting from S. P. may be of immediate experimental interests. i) The widths of D-meson and the predicted $\eta(1^+)$ are considerably small[35] ($<$ 10 Mev). ii) The identification of η (1^+) may be possible in $\bar{K}N$, $\bar{K}d$ or γ p-reactions, but it will be difficult in peripheral πN-reactions. iii) The production rates of $\eta'(0^+)$, D, E and f' will be quite small in πN- as well as the N exchange type $\bar{K}N$-reactions[35].

Finally we remark a few points on S. P. The applicability limit of S.P. is solely depends upon the magnitude of the pair effects. We conjecture that S.P. is applicable to the mutual interactions among hadrons with relatively low lying and well-defined configurations in the sense of § 2. Even in the case where the mass separations among the U (3)-multiplets belonging to the identical configuration are considerable, S. P. may be useful as the first approximation. Finally S. P. and N. R. P. are mutually compatible, but the former is not an automatic consequence of the latter. It is rather a sophistic combination of both the N.R.- and the quantized field theoretic descriptions of hadrons. Its foundation is not understood at the moment, though some comment on this point will be made in § 5.

§ 5. The models of urbaryon.

The quarks must have rather peculiar properties, if it should be identified with urbaryons. Besides the fractional values of their electric charges, they have to obey parastatistics to be reconciled with SU(6) symmetry[40]. In connection with these peculiarities, several modifications of the quark model have been proposed. They can be classified as follows *); i) a fermion triplet and a boson triplet[41], ii) two sets of fermion triplet[14)42], iii) three sets of fermion triplet[43)44], iv) a fermion triplet and a fermion singlet (quartet model)[45], and v) a fermion triplet and a boson singlet[46], etc.. Either integral or fractional charge values can be assigned in all of those modifications**).

It is possible to make the structure of mesons in those models essentially same as that of original quark model. The difference arises when we study the baryon structure. In the models i) and iv) very complicated structure must be assumed to treat the spin $\frac{1}{2}$ octet and spin $\frac{3}{2}$ decuplet on same footing as suggested by the sucess of SU(6) symmetry. These two models may not be favored in a generalization of the selection principle proposed in the preceding section too, when it is applied to processes containing baryons. The introduction of parastatistics is needed in the models of ii) and v) to treat the spin $^3/_2$ decuplet state as

*) The term fermion or boson in the classification is used to specify half integral or integral value of intrinsic spin, without regards to its statistics and particle nature.

**) Han and Nambu[43] gave definite integral values for urbaryons. But we feel that it is a superfluous assumption. When the charge values of the three sets of triplet are denoted as $(l, l\text{-}1, l\text{-}1)$, $(m, m\text{-}1, m\text{-}1)$ and $(n, n\text{-}1, n\text{-}1)$, these values must satisfy the condition $l+m+n=2$. The properties of the singlet state in the new SU(3) symmetry is identical for different charge values under this condition.

S-wave bound state of three urbaryons, similarly to the case of the quark model.

One of us[35] has suggested the possibility to discriminate experimentally some of the models by the investigation of electric dipole transition processes between two meson nonets with $(t\bar{t})$-structure such as $1^+ \to 1^- + \gamma$.

In most of the aspects the model iii) shows same characteristics as that of the quark model. We can construct a new SU(3) group by taking three sets of triplet of the ordinary U(3) group as members of the fundamental triplet representation of the new group. Every singlet state of the new SU(3) symmetry behaves as if it were composed of quarks and/or antiquarks obeying parafermi statistics of order 3. For example, three urbaryons in a baryon state are antisymmetric in new SU(3) symmetry space, therefore they should be symmetric in the product space of the other freedoms.

The reason why only singlet states are realizable may be most plausibly understood by the assumption[43] that the inter-urbaryon forces between fundamental triplets are mediated by vector fields belonging to octet of the new SU(3) group and to singlet of the ordinary U(3) group. Then the effective potential will have the form,

$$V_{tt} = \sum_{i=1}^{8} \Lambda_i^{(1)} \Lambda_i^{(2)} v(\boldsymbol{r}), \tag{13}$$

for the force between two urbaryons, and,

$$V_{t\bar{t}} = -\sum_{i=1}^{8} \Lambda_i^{(1)} \Lambda_i^{(2)} v(\boldsymbol{r}), \tag{14}$$

for the force between urbaryon and antiurbaryon. When we assume that $\langle v \rangle = \frac{3}{8} M_t$, the expectation value of the potential is $-M_t$ in sestet (tt) state, and $-2M_t$ in singlet $(t\bar{t})$ state, here, the multiplets are those of the new group. The force is repulsive in the other multiplets. When the kinetic energies and small corrections are neglected, the mass of the system which consists of arbitrary numbers of urbaryons and antiurbaryons can be expressed as,

$$m \approx \frac{1}{4} M_t \, [p^2 + pq + q^2 + 3(p+q)], \tag{15}$$

where (p, q) specifies the irreducible representation of the new SU(3) group. This formula means that the composite systems have very large mass values except in the case of singlet state of the new freedom, where the attractive potential almost cancels the masses of constituent particles. This model explains the selection principle stated in the preceding section naturally, since the field which mediates the primary force is octet of the new group while all mesons and baryons are singlet states.

We have not yet any concrete evidence to select one of those models as favorable one. It is hoped that experiments in near future will provide enough informations to discriminate them.

§ 8. Concluding Remarks

We have shown that rather reasonable agreements with experiment can be obtained from the standpoint stated in Introduction. Therefore we may hope that our fundamental approach is in the right directon in some sense. On the other hand, we cannot certainly exclude the possibility that the agreement is a fortuitous one. In this connection, it may be appropriate to make a remark that sometimes "*truth has come out of falsehood*". In any case we should exploit every possibility to clarify the present chaotic state of elementary particle physics. If the fundamental law of physics is to be altered, the wrong model of the present day may even happen to be a nice one in future. For example, before the application of quantum concepts to the atomic system, J. J. Thompson's atomic model was more easily conceivable than the Rutherford model. Even in the framework of composite model, the picture of hadrons is in no way unique. While we take the view in this report that the properties of hadron are dominantly determined by the structure of its inner part, there are various models and approaches where the properties are strongly influenced by the behavior of its cloud.

We conclude with our hope that our simple picture and scheme is useful as a kind of a pilot balloon in the phenomenology of hadrons.

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References

1) S. Sakata, Prog. Theor. Phys. 16, 686(1956).
2) S. Ogawa, Prog. Theor. Phys. 21, 209(1959).
M. Ikeda, S. Ogawa and Y. Ohnuki, Prog. Theor. Phys. 22, 715(1959) and 23, 1073(1960).
Y. Yamaguchi, Prog. Theor. Phys. Supple. 11, 1 and 37(1960).
3) K. Matumoto, Prog. Theor. Phys. 16, 583(1956).
S. Sawada and M. Yonezawa, Prog. Theor. Phys. 23, 662(1960) ;
K. Matumoto and M. Nakagawa, Prog. Theor. Phys. 23, 118(1960) ;
M. Ikeda, Y. Miyachi, S. Ogawa, S. Sawada and M. Yonezawa, Prog. Theor. Phys. 25, 1 (1960).
4) S. Tanaka, Prog. Theor. Phys. 16, 625 and 631(1956).
Z. Maki, Prog. Theor. Phys. 16, 667(1956).
Y. Fujii, Prog. Theor. Phys. 21, 232(1959).
5) Y. Ohnuki, Proc. 1960 Conf. High Energy Phys. pp. 843-850.
6) M. Gell-Mann, CTSL-20 (unpublished).
7) Y. Ne'eman, Nuclear Physics 26, 222(1961).
8) S. Okubo, Prog. Theor. Phys. 27, 949(1962).
9) M. Gell-Mann, Physics Letters 8, 214(1964).
10) G. Zweig, CERN preprint (unpulished).
11) F. Gürsey and L. A. Radicati, Phys. Rev. Letters 13, 173(1964).
12) B. Sakita, Phys. Rev. 136, B1765(1964).
13) Y. Ohnuki and A. Toyoda, Nuovo Cimento, 36, 1405(1965).

14) Y. Nambu, Proc. Second Coral Gables Conf. on Symmetry Principles at High Energy (W. H. Freeman and Co., San Francisco and London), 1965.
15) G. Morpurgo, Physics 2, 95(1965).
16) S. Ishida, Prog. Theor. Phys. 32, 922 (1964) and 34, 64(1965).
S. Machida and M. Namiki, Prog. Theor. Phys. 33, 125(1965).
Y. Miyamoto, Prog. Theor. Phys. 35, 175(1966).
17) K. Matumoto and M. Nakagawa, 3rd article of ref. 3.
18) G. Derrick and J. M. Blatt, Nuclear Physics 8, 310(1958).
G. H. Derrick, Nuclear Physics 16, 405(1960).
19) Y. Fujii, 3rd article of ref. 4·
20) J. J. Sakurai, Annals of Physics 11, 1 (1960).
21) Z. Maki, M. Nakagawa, Y. Ohnuki and S. Sakata, Prog. Theor. Phys. 23, 1174(1960).
22) J. Iizuka, Prog. Theor. Phys. 35, 117 and 309(1966).
23) R. H. Dalitz, Proc. Oxford International Conf. on Elementary Particles, 1965.
24) Y. Ohnuki, S. Otsuki and Y. Sumi, Soryushiron Kenkyu (Mimeographed Circular in Japanese) 26, 122(1962).
25) M. Taketani, S. Nakamura and M. Sasaki, Prog. Theor. Phys. 5, 730(1950) and 6, 581 (1951),
26) Y. Ne'eman, Phys. Rev. 134, B1355(1964).
27) K. Matumoto, Prog. Theor, Pheor, Phys. 35, 659(1966) and many others.
28) M. Yamazaki, Jour, Phys. Soc. Japan 21#9 in press.
29) H.A. Jahn and E. Teller, Proc. Roy. Soc. A161, 220(1937) and A164, 117(1938).
30) M. Yamazaki and S. Hori, Prog. Theor. Phys. 36, 1035 (1966)
31) T. F. Kycia and K. F. Riley, Phys. Rev. Letters 10. 266(1963).
32) T. Tati, H. Nagai and K. Okada, Prog. Theor. Phys. to be published.
33) S. Otsuki and S. Sawada, Prog. Theor. Phys. to be published.
34) Y. Nambu, Preludes in Theoretical Physics (North-Holland, Amsterdam 1966), p. 133–p. 142.
35) J. Iizuka, K. Okada and O. Shito, Prog. Theor. Phys. 35, 1061 (1966).
J. Iizuka, Prog. Theor. Phys. Supple. to be published.
36) C. Baltay *et al*, Phys. Rev. 145, 1103(1966) and the many works cited in this paper.
37) J. S. Lindsey and G. A. Smith, Physics Letters 20, 93(1966).
V. E. Barnes *et al*, Phys. Rev. Letters 15, 322(1965).
Suh Urk Chung *et al*, Phys. Rev. Letters 15, 325(1965).
For details on experimental data and references, See A. H. Rosenfeld *et al*, Rev. Mod. Phys. 37, 633(1965).
For theoretical analysis, See S. Okubo, Physics Letters 5, 165(1963).
S. L. Glashow and R. H. Socolov, Phys. Rev. Letters 15, 329(1965).
J. Iizuka *et al*, ref. 35).
38) Y. Y. Lee *et al*, Phys. Rev. Letters 11, 508(1963).
G. H. Trilling *et al*, Physics Letters 19, 427(1965).
39) K. W. Chen *et al*, Phys. Rev. 141, 1267(1966).
J. R. Dunning *et al*, Phys. Rev. 141, 1286(1966).
As for theoretical analysis, see S. Ishida, Kimiaki Konno and Hajime Shimodaira, preprints and in particular "Electromagnetic properties of Baryons and Quark Model" NUP-66-10.
40) O. W. Greenberg, Phys. Rev. Letters 13, 598(1964).
41) J. Schwinger, Phys. Rev. Letters 12, 237(1964).
F. Gürsey, T. D. Lee and M. Nauenberg, Phys. Rev. 135, 467(1964).
J. Iizuka, Ann. Sci. Kanazawa Univ. 2, 13(1965).
42) H. Bacry, J. Nuyts and L. van Hove, Phys. Letters 9, 279(1964).
43) Y. Nambu, See ref. 2)·
M. Y. Han and Y. Nambu, Phys. Rev. 139, B1006(1965).
Y. Miyamoto, Prog. Theor. Phys. Supple. Extranumber 187(1965).
S. Hori, Prog. Theor. Phys. 36, (1966) (in press).

44) Y. Katayama, I. Umemura and E. Yamada, Prog. Theor. Phys. Supple. Extranumber 564 (1965).
T. Tati, Prog. Theor. Phys. 35, 126(1966).
45) Z. Maki, Prog. Theor. Phys. 31, 331(1964).
Y. Hara, Phys. Rev. 135, B1047(1964).
46) S. Tanaka, Prog. Theor. Phys. 32, 859(1964) and 33, 762(1965).
F. Gürsey, T. D. Lee and M. Nauenberg, See ref. 41).