Progress of Theoretical Physics, Vol. 59, No. 4, April 1978

# How Can Several Baryoniums Be Narrow?

## ——*Mass Formula and Selection Rule of Unconventional Hadrons*——

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(Received November 25, 1977)

Mass formula of hadrons is given for their topological structure of the junction type. The result agrees with recent candidates for baryonium. By noticing the topological structure, the OZI rule and the FWR rule are unified into a selection rule (covalence rule). This rule forbids not only baryoniums to decay into the conventional mesons but also meson decay between three different kinds of baryoniums, which may be favorable to explain narrowness of rather many baryonium candidates. The covalence rule is uniquely interpreted by fission of oriented strings connecting constituents (quark and junction). The world of hadrons is characterized by a stepwise coupling, from the conventional baryons to baryoniums, and baryoniums to the higher unconventional hadrons.

## § 1. Introduction

Adopting the string picture as realization of the confinement mechanism and postulating that the strings is oriented with respect to triality and color (so that only the zero triality and color singlet hadron is produced by cutting the string), the authors have been examining the general structure and interaction scheme of hadrons of the junction type.[1)~4),5)] Hadrons of this type contain not only the conventional meson $M$ and baryon $B$ in Fig. 1 but three kinds of baryonium in Fig. 2 and other unconventional ones (Fig. 10). *The three-string junction* $J$ secures the equal qualification of the quark $q$ situated at an open end of the oriented (incoming) string whether it is inside $M$ or $B$. The junction is in accord with symmetry of three quarks inside $B$ of $SU(6)$ and neutralizes the three color indices,[1)] so that to any oriented hadron an expression by local gauge invariant operators of color gauge theory (QCD) by Rossi and Veneziano is given.[6)]

Our notation to specify hadrons of the junction type discussed in the text is

$$B_{N_q}^{N_J},\ M_{N_q}^{N_J},\ S_{N_q=0}^{N_J}\quad \text{and}\quad D_{N_q}^{N_J}\,, \tag{1·1}$$

where $N_q\equiv n_q+n_{\bar{q}}$ is the total number of $q$ and $\bar{q}$ and $N_J\equiv n_J+n_{\bar{J}}$ is that of $J$ and $\bar{J}$ (anti-junction) with the relations[1)]

$$n_B=(n_q-n_{\bar{q}})/3=n_J-n_{\bar{J}} \tag{1·2}$$

and

$$N_q=3N_J-2N_{JJ}\ \ (\text{for}\ \ N_J\neq 0)\,. \tag{1·3}$$

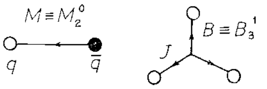


Fig. 1. Conventional hadrons, meson $M \equiv M_2^0$ and baryon $B \equiv B_3^1$.

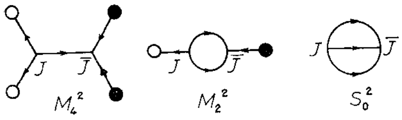


Fig. 2. Three kinds of baryonium.

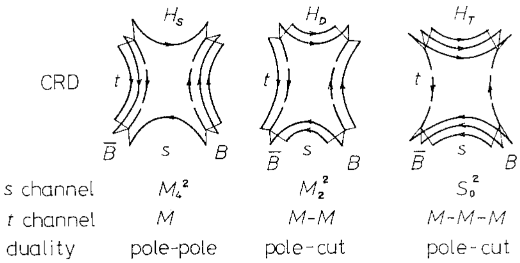


Fig. 3. $\bar{B}B$ duality scheme.

Here $n_B$ and $N_{JJ}$ respectively denote the baryon number and the total number of the inter-junction string. In (1·1) $B$ is baryon members with $n_B=1$, $M$ meson members with $n_B=0$ and $N_q \neq 0$, $S$ gluonic hadrons without quarks $(n_B=N_q=0)$ and $D$ dibaryons with $n_B=2$.*)

We have presented several arguments that *the junction is conserved and countable similarly to $q$.* In particular, the conserved $J$ practically substitutes the FWR (Freund-Waltz-Rosner) rule[7] and forbids the coupling $M_4^2 \leftrightarrow MM$ while allows $M_4^2 \leftrightarrow \bar{B}B$,[1] and the countable $J$ leads to the intercept $\alpha(0)$ of hadron trajectory of[2]

$$\alpha_{N_q,N_J}(0)=1-(N_q+N_J)/4 \qquad (1\cdot 4)$$

with $\alpha_M(0)=1/2$ and $\alpha_B(0)=0$. From the results we have proposed a new scheme of $\bar{B}B$ duality as Fig. 3.[2] (The motion of $J$ is represented by a broken line.) The three kinds of baryonium, not only $M_4^2$ but $M_2^2$ and $S_0^2$, appear in the intermediate states of $\bar{B}B$ channel, and couple to $\bar{B}B$ but decouple from $MM$.[1),**)] Because of the conserved and countable nature of $J$, we give the general term "constituent" to *both $q$ and $J$*, and call the rearrangement diagram CRD (constituent rearrangement diagram).

Recently much experimental and theoretical attention has been paid on baryoniums. We may be at the stage that baryoniums are opening the gate toward a wide world of unconventional hadrons. Being encouraged by such circumstances, we re-formulate the mass formula (§ 2) and elucidate the selective interaction scheme (§ 3) treated in previous papers.[1)~4)] The new points are as follows. The three kinds of baryonium are subject to the equal spacing mass relation

$$m(M_4^2)-m(M_2^2)=m(M_2^2)-m(S_0^2)=\delta \equiv 2m_B-m(M_4^2), \qquad (1\cdot 5)$$

where $m_B$ is the baryon mass, and, by taking the narrow peak at 1936 MeV as

*) Even the notation (1·1) is not sufficient enough to specify isomers (hadrons with the same $n_q$, $n_{\bar{q}}$, $n_J$ and $n_{\bar{J}}$ but different topological structure) such as for $M_4^4$ in Fig. 10 and also to represent multibaryons.[1)]

**) The three kinds of baryonium are the only mesons with one $J\bar{J}$ pair, so that another name "junctionium" may be conceptually more suitable than "baryonium" by Chew and Rosenzweig.[8)] input for $m(M_4^2)$,[9] the hadron mass is roughly given by[1]

$$m(N_q, N_J) \sim N_J m_B \tag{1·6}$$

in so far as the mass spacing $\delta$ is neglected compared with $m_B$. A selection rule for the three-hadron vertex, *covalence rule*,[3),4)] takes notice of the flow of the $J$ line at the vertex (see § 3). This rule does not only assure all the admitted results of the OZI (Okubo-Zweig-Iizuka)[10] and FWR rules but forbids the mesonic transition among the different kinds of baryonium

$$M_4^2 M_2^2 M,\ M_4^2 S_0^2 M \text{ and } M_2^2 S_0^2 M \tag{1·7}$$

even if the mass difference $\delta$ is larger than the pion mass. In § 4, it is shown that the covalence rule corresponds to the only allowed mechanism of "fission" of oriented strings linking constituents.

Based on the above results, phenomenological arguments of baryoniums and other unconventional hadrons are given in § 5. The forbidden pion decay among the different kinds of baryonium and the absence of baryoniums much lighter than $2m_B$ by (1·6) are favorable to explain the present trends that candidates for narrow baryoniums are increasing.[11] In § 6, characteristic features of our model are contrasted to those of other models[12),13)] almost ignoring the selective interaction. For example, Jaffe's four-body meson $(qq)_d(\bar{q}\bar{q})_{\bar{d}}$ of a bag model,[12] where $(qq)_d$ is the diquark cluster with dimensionality $d$ of color $SU(3)_c$, corresponds to $M_4^2$ for $d=3$ but to $M_4^4$ for $d=6$*. The latter is a hadron higher than baryoniums and does not decay into $\bar{B}B$ but to $BB\bar{B}\bar{B}$ by the covalence rule.

## § 2. Mass formula of unconventional hadrons

Hadrons of the junction type consist of three kinds of building block, the quark $q$ with one string, the junction $J$ and the inter-junction string between $J$ and $\bar{J}$. Then the simplest mass formula from additivity is as follows:

$$m(N_q, N_J, N_{IJ}) = m_q N_q + m_J N_J + v N_{IJ} = m_B N_J - \delta N_{IJ} \tag{2·1}$$

with

$$m_B \equiv 3m_q + m_J \quad \text{and} \quad \delta \equiv 2m_q - v\,, \tag{2·2}$$

where the last equality is due to $N_q = 3N_J - 2N_{IJ}$ (for $N_J \neq 0$) of (1·3), $m_B$ is the baryon mass and $\delta$ corresponds to an "attraction" by the inter-junction string. Equation (2·1) leads to

$$2m_B - m(M_4^2) = m(M_4^2) - m(M_2^2) = m(M_2^2) - m(S_0^2) = \delta\,, \tag{2·3}$$

*the equal spacing mass relation* among the three kinds of baryonium.

For $\delta \ll m_B$ as below, the mass of unconventional hadrons is approximately given *by the number of $J$* as $m(N_q, N_J) \sim m_B N_J$ (Eq. (1·6)). Namely, the baryonium, the five-body baryon $B_5^3$ and the dibaryon $D_6^4$ in Fig. 10 are expected to have masses respectively of about $2m_B$, $3m_B$ and $4m_B$. Because of these high values, we have assumed the linear mass formula in (2·1).

Somewhat more in detail, if we assign the established narrow peak at 1936 MeV with $\Gamma=(4\sim 8)$ MeV and probably $I=1$[9] to the ground state of $M_4^2$ and take $m_B=(m_N+m_\Delta)/2=1085$ MeV (averaged by the $SU(6)$ scheme), we have from (2·1)

$$m(M_4^2)=1935\text{ MeV (input)},\ m(M_2^2)\sim 1700\text{ MeV and } m(S_0^2)\sim 1465\text{ MeV} \tag{2·4}$$

with $\delta\sim 235$ MeV. The mass difference in the quark level could be taken into account by

$$m=m_BN_J-\delta N_{IJ}+\Delta m_\lambda N_\lambda+\Delta m_c N_c\,, \tag{2·5}$$

where $N_{\lambda(c)}$ is the total number of the strange (charm) quark $\lambda(c)$ and $\Delta m_{\lambda(c)}$ is the mass difference between $\lambda(c)$ and nucleonic quark $\mathfrak{N}$. Assuming $\Delta m_\lambda=150$ MeV and $\Delta m_c\simeq 1.2$ GeV, we give some phenomenologies in §5. Charmed unconventional hadrons are expected heavier than 3 GeV.

By the Padé approximation to QCD, Migdal obtained the hadron mass from the zero of the Bessel function:[14]

$$J_{d-2}(2Rm)=0\,, \tag{2·6}$$

where $d=(3/2)N_q+2N_{IJ}$ is the dimension of the local gauge invariant operators.[15] As the Bessel zero depends almost linearly on $d$, the mass obtained from (2·6) is similar to that by (2·1)[3]: Using again (1·3),

$$m\sim m_0 d=m_0[(3/2)N_q+2N_{IJ}]=m_BN_J-\delta N_{IJ} \tag{2·7}$$

for $m_B=9m_0/2$, $\delta=m_0$, and $m_0=m_0(R^{-1})\sim 0.24$ GeV for $2R\sim 5$/GeV to fit the $\rho$ meson mass.[14] (By (2·1) the conventional meson mass $m(N_q=2, N_J=N_{IJ}=0)$ $=2m_q$ is arbitrary as $m_q$ itself is free because of (1·3)).

## §3. Selection rule (covalence rule) for three-hadron vertex

At a given hadron vertex, *the covalence rule* is expressed in terms of *both q and J(constituent) lines* as follows:

*Rule A.* No constituent line is connected with an anti-constituent line from the same hadron.

*Rule B.* Each of the three hadrons meeting at the vertex exchanges at least one constituent line with each of the remaining two hadrons.

In other words, every constituent (*q and J*) line shares two hadrons (Rule A) and any pair of hadrons shares at least one (*q and/or J*) constituent line (*covalence* (Rule B)).

Figure 4 gives examples of the covalence rule. All allowed three hadron vertices among $M$, $B$ and baryonium are as follows:

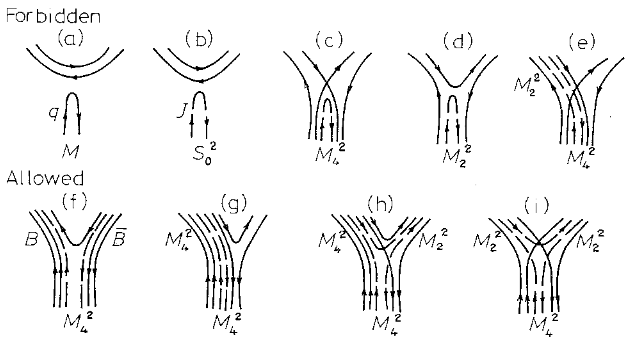


Fig. 4. Examples of the covalence rule.

$$MMM,\ M\overline{B}B\,, \tag{3·1a}$$

$$M_4^2\overline{B}B,\ M_2^2\overline{B}B,\ S_0^2\overline{B}B\,, \tag{3·1b}$$

$$M_4^2M_4^2M,\ M_2^2M_2^2M\,, \tag{3·1c}$$

$$M_4^2M_4^2M_4^2,\ M_2^2M_2^2M_2^2,\ S_0^2S_0^2S_0^2,\ M_4^2M_4^2M_2^2,\ M_4^2M_4^2S_0^2\,,$$

$$M_4^2M_2^2M_2^2,\ M_2^2M_2'^2S_0^2\,. \tag{3·1d}$$

The forbidden vertices of interest are

$$M_4^2MM,\ M_2^2MM,\ S_0^2MM\,, \tag{3·2a}$$

$$M_4^2M_2^2M,\ M_4^2S_0^2M,\ M_2^2S_0^2M\,. \tag{3·2b}$$

Physical significance of the covalence rule is as follows.

i) The rule assures all the admitted results of the OZI and FWR rules. The disconnected diagram is forbidden. If one replaces the word "constituent" by quark, the expression of Rule A and B is identical with that of the FWR rule.

ii) Not only the four-body meson $M_4^2$ but the other kinds of baryonium ($M_2^2$ and $S_0^2$) couple to $\overline{B}B$ (3·1b) but decouple from $MM$ (3·2a).

iii) The meson decay among the different kinds of baryonium is forbidden (3·2b).

iv) The last, but not the least, significance is that the covalence rule is interpreted into a simple and unified language of oriented strings linking constituents, as discussed in the next section.

## § 4. Interation mechanism of string

While the covalence rule A and B is stated in terms of the constituent ($q$ and $J$) flow, the rule implies a unified interaction mechanism of the string. Possible decay mechanisms are classified into (i) fission, (ii) internal cross over (iii) internal fusion, (iv) rip up, etc.

*Rule* $\alpha$ The three-hadron vertex $abc$ is allowed only when the three decay processes, $a\to\overline{b}\overline{c}$, $b\to\overline{c}\,\overline{a}$ and $c\to\overline{a}\overline{b}$, are symmetric in the meaning that they occur

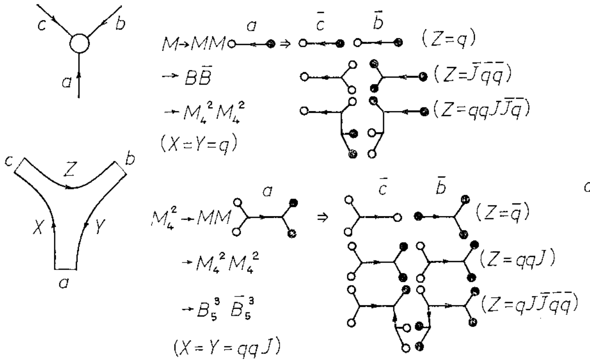


Fig. 5. Single fission $F_S$ and the covalence rule.

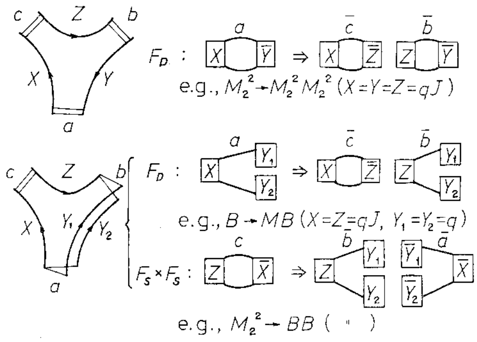


Fig. 6. Two fissioning strings under the covalence rule.

by the same kind of mechanism.

*Rule* $\beta$ The decay $a \to \bar{b}\bar{c}$ is caused *only by the fission* of oriented strings of the parent hadron explained below.

*Fission of string*

Before a general explanation, we give some simple versions of the fission with examples in Figs. 5~8.

*Single fission* $F_S$ cuts one string of a hadron $a$ into two hadrons $\bar{b}$ and $\bar{c}$ by creating a pair of $Z$ and $\bar{Z}$, where $Z$ is an irreducibly connected system of $q$, $J$ and string with at least one constituent ($N_q + N_J \neq 0$ in $Z$) and is orientedly linked only to the parent string. The simplest $F_S$ is observed in the MMM vertex, where the string linking $q$ and $\bar{q}$ is cut by an $\bar{q}q$ pair ($Z=q$). Figure 5 shows the general $F_S$, that applies to the case of one fissioning string satisfying the covalence rule with $a=(X\bar{Y})$, $b=(Y\bar{Z})$ and $c=(\bar{Z}X)$. Important nature not only of $F_S$ but of the general fission is that covalence of child hadrons $\bar{b}$ and $\bar{c}$ is assured because of $N_q + N_J \neq 0$ in $Z$ and that any hair pin lines are excluded since $\bar{Z}$ is nothing but anti-$Z$.

*Double fission* $F_D$ cuts two strings linking $X$ and $\bar{Y}$ of a hadron $a=(X\bar{Y})$ into two by creating a pair $Z\bar{Z}$. We require for $Z$, $N_q + N_J \neq 0$ similarly to that of $F_S$. There are two cases depending on whether $X$ and $\bar{Y}$ are irreducible or one of them, say $\bar{Y}$, is reducible as Fig. 6.

*Simultaneous combination of* $F_S$, $F_S \times F_S$, cuts each of two strings of $c=(Z\bar{X})$ by $F_S$ simultaneously as Fig. 6, where $Z$ and $\bar{X}$ are both irreducible.

If $X$ (and $\bar{Y}$) in the second (first) case of Fig. 6 contains at least one constituent similarly to $Z$, the vertex is allowed by Rule $\alpha$ of symmetry. Thus Fig. 6 presents the topological structure of all allowed vertices in the case of two fissioning strings. In the second case $F_D$ and $F_S \times F_S$ are complement each of the other.

It is straight forward to extend the above arguments to multiple fission, *triple*

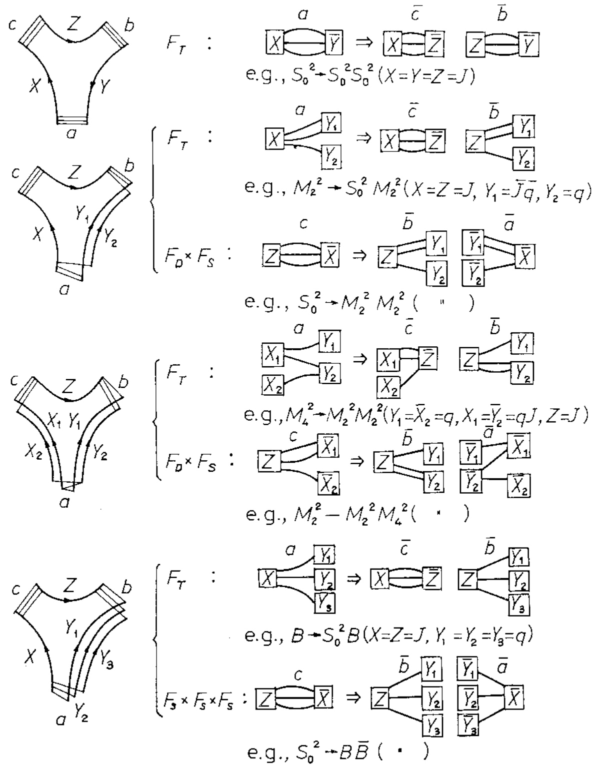


Fig. 7. Three fissioning strings under the covalence rule.

*fission* $F_T$, etc. and to *simultaneous combinations of allowed fissions*, $F_S \times F_S \times F_S$, $F_D \times F_S$, etc. Figure 7 covers all allowed vertices with three fissioning strings.

Summarizing, the fission of Rule $\beta$ is to cut simultaneously one hadron into two (not more), by creating a set of pairs of irreducible systems $Z_i$ $(i=1, 2, \cdots)$ on an arbitrary (nonzero) number of the parent strings keeping the orientation, where every $Z_i$ contains *at least* one constituent. When all three decays are due to the fission by Rule $\alpha$, the covalence rule holds, and *vice versa*. The reverse mechanism, *fusion*, by which a set of $Z_i$ and $\bar{Z}_i$ from *different* hadrons annihilate each other to form a hadron, is also the allowed mechanism of the string.

*Forbidden interaction mechanism*

We may ask what happens if $X$ in $F_D$ (Fig. 6) contains no constituents $(N_q+N_J=0)$. The orientation of the string through this *null* $X$ is definite as Fig. 8, so the decay $b \to \bar{c}\bar{a}$ is caused by *internal cross over* (ICO), a mechanism other than the fission, and leads to lacking in covalence of $\bar{c}$ and $\bar{a}$ though both $\bar{c}$ and $\bar{a}$ are respectively an oriented hadron. Thus ICO violates Rule $\alpha$ and $\beta$. The vertices $M_4^2 M_2^2 M$ and $M_2^2 S_0^2 M$ in (3·2b) together with $S_0 a\bar{a}$ such as $S_0 MM$

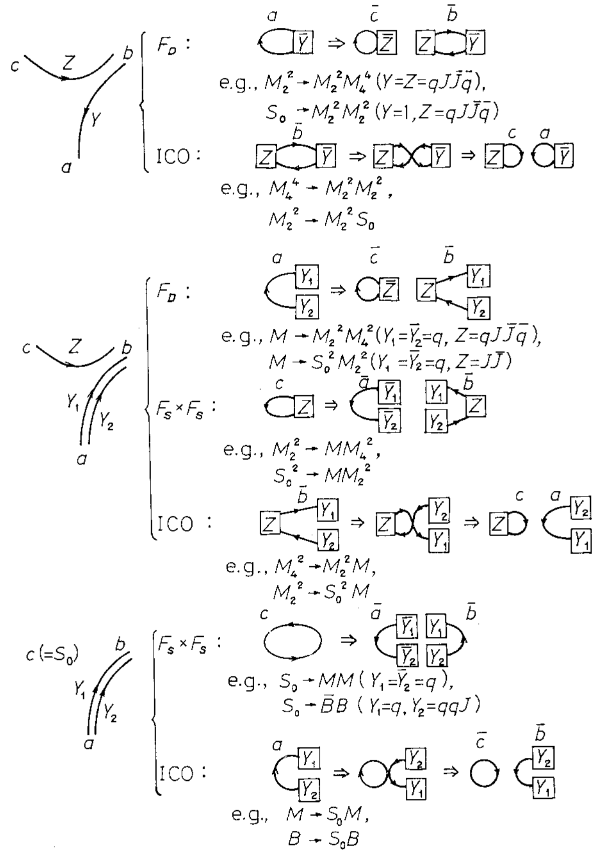


Fig. 8. Internal cross over to break the covalence rule. This figure corresponds to putting $X=1$ (the *null* $X$) and, in the last case, also $Z=1$ in Fig. 6.

in Fig. 4(a) and $S_0B\bar{B}$ belong to this forbidden category, where $S_0$ is the simple string without constituents. The vertex $S_0S_0S_0$ caused only by ICO is forbidden by Rule $\beta$ though it exceptionally satisfies Rule $\alpha$. Thus Pomeron should not be considered any decay product but a tube in the unphysical channel.

The other forbidden mechanism is *internal transition*, by which we mean creation and annihilation of $q$ and $\bar{q}$ and/or $J$ and $\bar{J}$ in a single hadron, or more generally, of a set of pairs of irreducible systems of $Z_i'$ *with strings linking the pair*. Above all, the internal transition is forbidden for any oriented hadron to be stable ($S_0 \not\leftrightarrow M$, $M \not\leftrightarrow M_2^2$, $M_2^2 \not\leftrightarrow M_4^2$, $S_0 \not\leftrightarrow S_0^2$, etc.). At the allowed vertex, the internal transition is also forbidden, otherwise the unwanted hair pin lines by Rule A arise as readily understood.

*Allowed direct process*

This is the process by which two or more hadrons change into more than one hadrons directly, i.e., without any intermediate single hadron.

The double fission or fusion $F_D$ on two *open* strings, or on two strings from *different* hadrons (reducible $X$ and $\overline{Y}$ in Fig. 6) is *rip up* or *open fission and fusion* mechanism as Fig. 9 The examples are

$$MM \leftrightarrow \overline{B}B,\ MB \leftrightarrow BM_4^2$$

and

$$\overline{B}B \leftrightarrow M_4^2 M_4^2 . \qquad (4\cdot1)$$

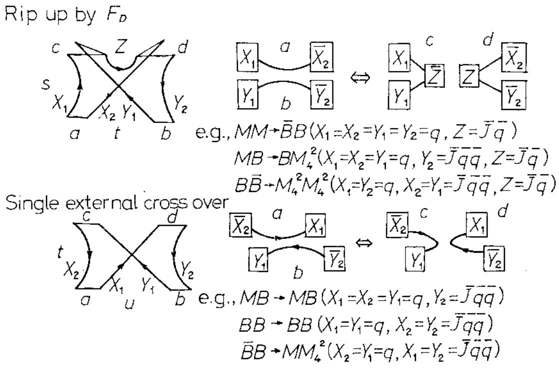


Fig. 9. Direct processes.

Here the other two channels proceed via single hadron exchange (dual). The first of (4·1) occurs in $t$ channel of $MB$ reactions with the $B$ exchange in $s$ and $u$ channels, and in $t$ channel of $H_D$ in Fig. 3.

Figure 9 also shows *external cross over* (ECO), whose examples are

$$MM \leftrightarrow MM,\ MB \leftrightarrow MB,\ BB \leftrightarrow BB \text{ and } \overline{B}B \leftrightarrow MM_4^2 . \qquad (4\cdot2)$$

The third above occurs in $u$ channel of $H_S$ in Fig. 3. The other two channels are also due to single hadron exchange.

The arguments apply to the more *open* strings such as $\overline{B}B \leftrightarrow MMM$ by $F_T$ ($t$ channel of $H_T$) and $BB \leftrightarrow BB$ by the double ECO ($u$ channel of $H_D$ in Fig. 3).

## § 5. Phenomenological aspects of baryonium and unconventional hadrons

We start with giving mass of some unconventional hadrons (Table I) by (2·1, 5) and Regge intercept (Table II) by (1·4), together with their topological structure (Fig. 10).

The theoretical results in the preceding sections are essential, we believe, to explain *narrowness* of rather *many* (several or even more) states of baryonium, although there is no doubt that more and more broad states should exist:

i) Three kinds of baryonium, $M_4^2$, $M_2^2$ and $S_0^2$, in Fig. 2.

ii) The forbidden pion decay among the different kinds of them by (3·2b).

iii) Absence of baryoniums much lighter than $2m_B$ by (2·4).

Keeping these results in mind, some arguments on phenomenological aspects of baryonium and unconventional hadrons, that are interesting to our model, are given, though well established information on them is rather scanty.

A) *Baryonium below $\overline{N}N$ threshold* Recently, three narrow peaks of $\gamma$ ray spectrum from stopped $\bar{p}$ and $p$ (the atom of $\bar{p}$ and $p$) have been reported at $E=183$, 216 and 420 MeV.[16] This strongly indicates baryoniums of 1683, 1646 and 1394 MeV by $(\bar{p}p)_{\text{atom}} \to \gamma(\text{baryonium})$. It is tempting to assign them to the

Table I. Mass and quark configuration of unconventional hadrons by (2·1) and (2·5).

Baryonium ($N_J=2$, $n_J=n_{\bar{J}}=1$)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $M_4^2$ | $\mathcal{NN}\bar{\mathcal{N}}\bar{\mathcal{N}}$ | $\mathcal{N}\lambda\bar{\mathcal{N}}\bar{\mathcal{N}}$ | $\mathcal{N}\lambda\bar{\mathcal{N}}\bar{\lambda}$, $\mathcal{NN}\bar{\lambda}\bar{\lambda}$ | $\mathcal{N}\lambda\bar{\lambda}\bar{\lambda}$ | $\lambda\lambda\bar{\lambda}\bar{\lambda}$ | $M_2^2$ | $\mathcal{N}\bar{\mathcal{N}}$ | $\mathcal{N}\bar{\lambda}$ | $\lambda\bar{\lambda}$ | $S_0^2$ | 1465 |
| | 1935 | 2085 | 2235 | 2385 | 2535 | | 1700 | 1850 | 2000 | | |

Baryon with $N_J=3$ ($n_J=2$, $n_{\bar{J}}=1$)

| | | | |
|---|---|---|---|
| $B_5^3$ | $\mathcal{NNNN}\bar{\mathcal{N}}$ | $B_3^3$ | $\mathcal{NNN}$ |
| | 2785 | | 2550 |

Dibaryonium ($N_J=4$, $n_J=2$, $n_{\bar{J}}=2$),

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $M_6^4$ | $\mathcal{NNN}\bar{\mathcal{N}}\bar{\mathcal{N}}\bar{\mathcal{N}}$ | $M_4^4$(ring), $M_4^{4\prime}$, $M_4^{4\prime\prime}$ | $\mathcal{NN}\bar{\mathcal{N}}\bar{\mathcal{N}}$ | $M_2^4$, $M_2^{4\prime}$ | $\mathcal{N}\bar{\mathcal{N}}$ | $S_0^4$ | 2930 |
| | 3635 | | 3400 | | 3165 | | |

Dibaryon with $N_J=4$ ($n_J=3$, $n_{\bar{J}}=1$)

| | |
|---|---|
| $D_6^4$ | $\mathcal{NNNNNN}$ |
| | 3635 |

Table II. Regge intercept $\alpha(0)$ of hadrons by (1·4).

| | $S_0$ | $M$ | $B$ | $M_4^2$, $M_2^2$, $S_0^2$ | $B_5^3$, $B_3^3$ | $M_6^4$, $M_4^4$, $M_2^4$, $S_0^4$ | $D_6^4$ |
|---|---|---|---|---|---|---|---|
| $\alpha(0)$ | 1 | 1/2 | 0 | −1/2 0 1/2 | −1 −1/2 | −3/2 −1 −1/2 0 | −3/2 |

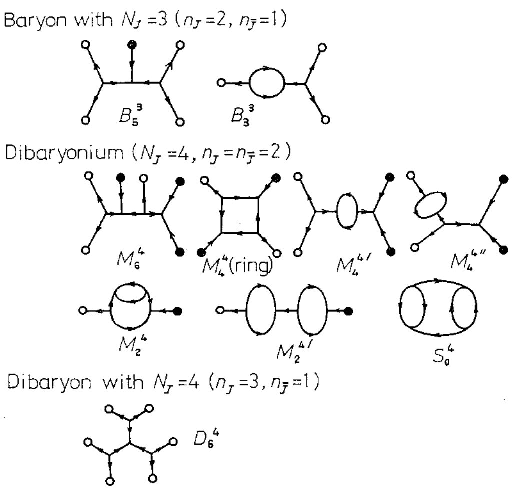


Fig. 10. Topological structure of some unconventional hadrons.

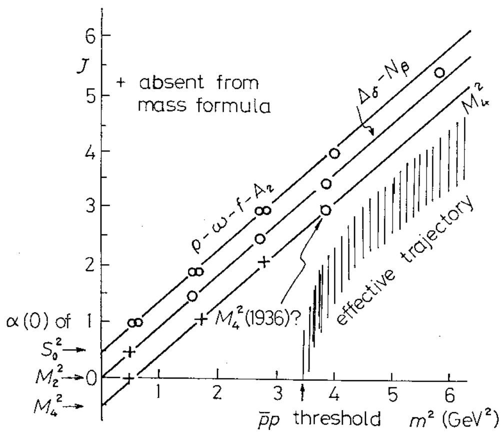


Fig. 11. Leading trajectories of $M$, $B$ and $M_4^2$, and the $\bar{N}N$ effective peripheral trajectory from $l<J<l+1$ with $\sqrt{l(l+1)}=kb_0$ and $b_0=5$/GeV, where $k$ denotes the cm momentum of the $\bar{N}N$ system.

lowest $M_2^2$ and $S_0^2$ by (2·4), or the $I=0$ and $I=1$ members of $M_2^2(1700; \mathfrak{N}\bar{\mathfrak{N}})$ and $S_0^2(1465)$ of Table I respectively. If our mass formula is correct, it is impossible to observe a similar line spectra from $(\pi^- p)_{\text{atom}}$, $(K^- p)_{\text{atom}} \to \gamma B_5^3$, $\gamma B_3^3$ and $(\Sigma^- p)_{\text{atom}} \to \gamma D_6^4$.

B) *Intercept and slope* Starting with the intercept of (1·4) or Table II, the peak at 1936 MeV[9] situates at spin $J=3$ of the $M_4^2$ trajectory as Fig. 11 if all the linear tree family of hadrons $(M, B, M_4^2, B_5^3, M_6^4, \cdots)$[1] has the universal slope $\alpha' \simeq 1/\text{GeV}^2$. It should be narrow, lying near the $\bar{N}N$ threshold and high above the effective trajectory of the peripheral $\bar{N}N$ interaction at the impact parameter $b_0 \simeq 5/\text{GeV}$,[1] and forbidden to decay not only into $MM$ but into $M_2^2 M$ and $S_0^2 M$. If the peak situates lower, say, at $J=2$, it is estimated broad ($\sim$tens MeV) because of the weaker centrifugal barrier to $\bar{N}N$. Several broad enhancements, that Carter et al. have pointed out in the $S(\sim 1940\text{ MeV})$ $T(\sim 2150\text{ MeV})$ and $U(\sim 2310\text{ MeV})$ regions from their analyses of $\bar{p}p \to \bar{p}p$ and $\bar{p}p \to \pi^+\pi^-$,[17] may be lower baryoniums and/or the conventional mesons $M$ overlapping the peripheral effective trajectory.

A possibility of slopes of $M_2^2$ and $S_0^2$ is that they are also universal. Then $M_2^2$ and $S_0^2$ with the mass (2·4) both situates at $J=3$, the maximum possible spin composed from $q$ and the inter-junction string if the latter carries the unit angular momentum.[15] Baryoniums may satisfy asymptotic planarity.[18] Or the slope becomes the flatter as the more complicated structure of hadrons, e.g., a simple relation by Rossi and Veneziano is[6]

$$\alpha'_{N_q, N_J} = 2\alpha'/(4+N_J-N_q) = \alpha'/(2+N_{JJ}-N_J) = \alpha'/(1+N_R). \tag{5·1}$$

The last equality is due to[1]

$$N_R = N_{JJ} - N_J + 1 \quad (\text{for } N_J \neq 0), \tag{5·2}$$

where $N_R$ denotes the number of the string ring of the hadron. In this case both $M_2^2$ and $S_0^2$ may have $J=1$. By Uehara, $\alpha'$ may be more dynamical for unconventional hadrons in the dual unitarization scheme.[19] At any rate, the slope is important for the topological structure of hadrons to give a measure of the effective spring constant of open and closed strings.

C) *Baryonium containing strange quark pair* Two narrow peaks at 2020 MeV and 2204 MeV have been observed in the $\bar{p}p$ invariant mass spectrum from $\pi^- p \to \pi^- p_f p\bar{p}$ when $\pi^- p_f$ form bands of $\Delta(1236)$ and $N^*(1520)$, where $p_f$ denotes the fast moving proton.[20] At first sight, these peaks with the large masses could not be narrow because of the allowed decay into $\bar{N}N(\Gamma \sim 10^2\text{ MeV})$. But if they contain a strange quark pair as $M_2^2(2000; \lambda\bar{\lambda})$ and $M_4^2(2235; \mathfrak{N}\lambda\bar{\mathfrak{N}}\bar{\lambda})$ in Table I, they could be narrow since they decay by breaking the covalence rule as Fig. 12.

D) *Photon-baryonium coupling* As is well known, the photon breaks the OZI rule, and peaks of the conventional mesons are observed in $\bar{e}e$ annihilation experiment. Baryonium productions by $\bar{e}e$ colliding beam*) offer an interesting problem

*) A narrow peak at 1820 MeV has been reported in $\bar{e}e$ annihilation.[21]

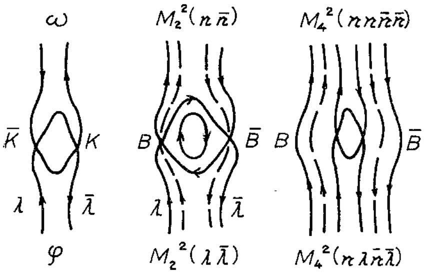


Fig. 12. Breaking of the covalence rule.

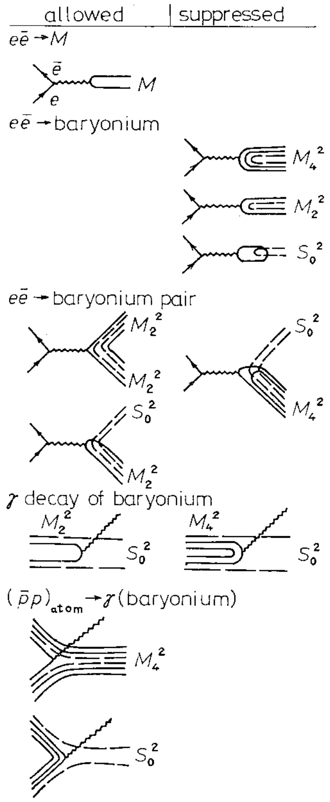


Fig. 13. Photon-baryonium coupling.

on the covalence rule. In $M_2^2$ production, for example, the extra hair pin of $J$ line is required in addition to the hair pin type $q$ line coupling to $\gamma$ as in Fig. 13. The extra hair type constituent line is expected to suppress the ratio of production of $M_2^2$ or $M_4^2$ to $M$ more than that estimated by the phase space factor alone. In this way we have

$$\begin{aligned} \bar{e}e &\to M \text{ (allowed)}, \\ &\to M_4^2, M_2^2 \text{ (suppressed compared with } M), \\ &\to S_0^2 \text{ (absent)}.^{*)} \end{aligned} \tag{5·3}$$

$$\begin{aligned} \bar{e}e &\to M_4^2M_4^2,\ M_2^2M_2^2,\ M_4^2M_2^2,\ M_2^2S_0^2 \text{ (allowed)}, \\ &\to M_4^2S_0^2 \text{ (suppressed compared with the above)}. \end{aligned} \tag{5·4}$$

The photon decay between baryoniums is allowed except for $\gamma M_4^2S_0^2$ and $\gamma S_0^2S_0^2$. The above referred $(\bar{p}p)_{\text{atom}}\to\gamma$(baryonium) is also allowed.

E) *Dibaryon* Contrarily to the expectation from idealized duality, the exotic $NN$

*) But a small mixing between $M_2^2$ and $S_0^2$ leads to a small formation cross section of $\bar{e}e\to S_0^2$.

channel has several structures at around 2 GeV, which are largely inelastic and very broad ($\Gamma \sim 10^2$ MeV).[22] On the other hand, the dibaryon $D_6^4$ in Fig. 10 decouples from $NN$ and is narrow if $m(D_6^4) < 4m_N$. We would not regard the deuteron and the $NN$ structures as the dibaryon. Rather, they could be explained, so to speak, by some residual interaction since no attraction is expected in $NN$ channel in the limit of exchange degeneracy between the vector and tensor trajectories. For example, the deuteron and the $NN$ structures could not be formed without the one pion exchange force with the "exceptionally" long range by the small pion mass, and its smallness may be presumably due to chiral dynamics, a concept that is not easily incorporated into exchange degeneracy.*)

## § 6. Concluding remarks

The most characteristic feature of our model for the wide world of hadrons is that the coupling among them is *stepwise* (*sequential*) because of the selection rule. Consider allowed productions of unconventional hadrons making use of the conventional beam and target:

$$\begin{aligned}
\bar{B}B &\to MM_4^2 \quad (B \text{ exchange}),\\
&\to M_4^2 M,\ \bar{B}B,\ \cdots\\
MB &\to M_4^2 B_5^3 \quad (M_4^2 \text{ exchange}),\\
&\to B_5^3 M,\ BM_4^2,\ \cdots\\
BB &\to M_4^2 D_6^4 \quad (B_5^3 \text{ exchange}),\\
&\to D_6^4 M,\ B_5^3 B,\ \cdots
\end{aligned} \tag{6·1}$$

The production rate may be small because of the high mass of unconventional hadrons at low energies and of the suppressed exchange of unconventional hadrons at high energies. In the alternative way, they may be found in formation experiment through forbidden processes as

$$MB \to B_5^3 \quad \text{and} \quad BB \to D_6^4 . \tag{6·2}$$

This stepwise feature is to be compared with the picture that baryoniums are nothing but the counter bound states to the $NN$ system through one boson exchange forces (quasinuclear state).[13] In this picture the centrifugal barrier is the only mechanism to suppress the baryonium decay. But the barrier could explain narrowness of *few* states lying a little above the $\bar{N}N$ threshold with high spin, even if no lower lying states (lower by the pion mass or more) exist.

In the bag picture, difference between the conventional and unconventional hadrons should, in principle, be no more than quantitative as the difference is reduced to that of the quark number $N_q$ within the bag. As we have discussed,

*) An interpretation that the $NN$ structures, if not all, come from threshold effects is not excluded.

$N_q$ alone is unable to discriminate different topological structures. We compare in Fig. 14 our topological clusters with multi-quark clusters within a bag noticing the $SU(3)_c$ representation $d$. The diquark $(qq)_d$ is the building block of Jaffe's $q^2-\bar{q}^2$ meson.[12] (i) $(qq)_3$ (antisymmetric representation) is the lowest $SU(3)_c$ representation, and $(qq)_3-(\bar{q}\bar{q})_{3^*}$ corresponds to $M_4^2$, a member of baryoniums. (ii) $(qq)_6{}^*$ (symmetric representation) does not correspond to the topological cluster with $N_J=1$ and one open string but to that with $N_J=4\,(n_J=n_{\bar{J}}=2)$ with two open strings, since

$$(qq)_{6^*}(J\bar{J}J\bar{J})=q_i q_n \varepsilon^{ijh}\varepsilon_{jkm}\varepsilon^{mnf}\varepsilon_{flh}$$

$$=(q_k q_l+q_l q_k)\in 6^*. \qquad (6\cdot3)$$

By linking $q$ and $\bar{q}$ belonging to $6^*$ to the ends of the two open strings respectively, $M_4^4$ in Fig. 10 corresponds to $(qq)_6{}^*-(\bar{q}\bar{q})_6$. (iii) While two quarks with the common $J$ can be reduced topologically to the diquark $(qq)_3$ by contracting the strings, $(qq)_6{}^*$ cannot because of the string ring. This is a difference between our picture and Jaffe's. (iv) By the covalence rule $M_4^4$ cannot decay into $\bar{B}B$ but to $M_4^2M_4^2$, $B\bar{B}_5{}^3$, $\bar{B}B_5{}^3$ and $BB\bar{B}\bar{B}$. So $M_4^4$ may be called *dibaryonium*, not baryonium. There are seven different topological structures of the dibaryonium $(N_J=4\,(n_J=n_{\bar{J}}=2),\, n_B=0)$ as Fig. 10, and may be observed at the mass band of about $4m_N$.

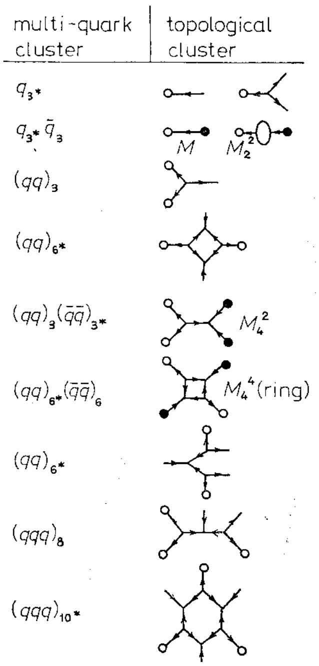


Fig. 14. Multi-quark cluster and topological cluster with the same $SU(3)_c$ representation.

We feel that ignorance of difference of topological structure of hadrons may be misleading. Without taking account of the topological structure it would be impossible to unify the old OZI rule, on which a highlight is being shed after the discovery of the new quark world ($J/\psi$ and $\Upsilon$), and the selective interaction of the old quark world (baryonium) into a single rule such as the covalence rule. But it is an open problem how the string allows only the fission mechanism.

## Acknowledgements

The authors gratefully acknowledge stimulating discussions with Professor M. Uehara, Professor F. Toyoda and the members of their group.

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