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P5b Particle Spectroscopy, Theoretical

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§1. Introduction

There were only five particles on the list of the elementary particles, when Professor Yukawa, the President of this Conference, invented the pions forty four years ago.[1]

At that time the proton, neutron and electron were considered to be the basic constituents of matter, and nuclear forces were proposed to be mediated by pions.

Since then, an enormous number of particles have been discovered. For example, there were an exciting discovery of the *Y* particle last summer and confirmation of *Y'* we have just heard at this Conference.

Now the colored quarks with flavors are considered to be the basic constituents of hadrons, and we have quantum chromodynamics (QCD) as a promising candidate of the dynamics of the strong interaction.

Today I will try to report on the progress of particle spectroscopy from this point of view. I will speak about

charmonium,

R,

spectroscopy of old hadrons and QCD,

charmed hadrons,

baryonium,

and

dibaryons.

§2. Charmonium

At first let us discuss charmonium. We show the levels and branching ratios of the known charmonium in Fig. 2. I.[2,3]

Qualitatively the level structure of the *Jj(p* family of new particles can be explained as charmonium, *i.e.*, as a charmed quark-antiquark *(cc)* system bound nonrelativistically by a potential suggested by the idea of QCD. However, there are still two serious problems in this model, the hyperfine splittings of 15 and *2S* states and the magnitudes of the

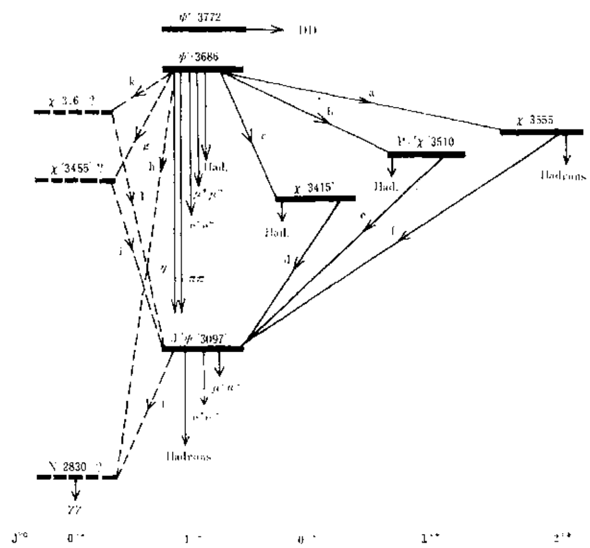

Fig. 2. **1.** Charmonium.
Branching ratios of Υ-decays; $a=7\pm2\%$, $b=7\pm2\%$, $c=7\pm2\%$, $d=16\pm3\%$, $e=23.4\pm0.8\%$, $f=3.3\pm1.0\%$, $g<2.5\%$, $h<1.0\%$, $ig\approx0.5\%$, $j<1.7\%$, $kl=0.28\pm0.12\%$. Data are taken from refs. 2, 3 and particle data group, Phys. Lett. **75B** (1978) i.

Ml transition rates if JST(2.83) and %(3.455) are to be identified with the *VS₀* and 2^1S_0 state.

The contribution of the spin-spin interaction,[4] *(327caₛl9m²꜀)s₁'S₂ô(r),* arising from the exchange of a single color-gluon to the hyperfine splitting is given by

$$\Delta M=\frac{32\pi\alpha_s}{9m_c^2}|\psi(0)|^2\approx\begin{cases}36\text{ MeV for }1S\\15\text{ MeV for }2S,\end{cases}\qquad(2.1)$$

for ra꜀^1.65GeV and aₛ=0.19. Here, *aₛ(ml)=0A9* was obtained by applying the formula[5] *Tiy* hadrons) « *R(V -> ggg)=* (160/81)**(7r**²-9)(a³/M²)|^(0)|² to f(//^ hadrons). Here, we used the magnitudes of |^(0)|² determined from[6] **r**(F-» *p⁺p~)=* 16^a²e²|^(0)|²/M². The predicted mass differences (2.1) should be compared with the experimental values of 270 and 230 MeV, respectively.

In the nonrelativistic approximation, the decay width of the Ml transition *Jjcp^XA-j* is predicted to be 29 keV, while experimentally it is < 1 keV.

Let us discuss these problems.

The potential suggested by the idea of QCD consists of spin independent part and spin dependent part,

$$U(r)+U_{\rm spin}(r). \tag{2.2}$$

Traditionally spin independent potential *U(r)* is a sum of a phenomenological long-range confining potential assumed to vary linearly with distance and a short-range Coulomb type potential arising from the exchange of a single color-gluon between the quarks,[7]

$$U(r)=ar-\frac{4}{3}\frac{\alpha_s}{r}. \tag{2.3}$$

Since the confining potential is considered to arise from multiple-gluon-exchanges, it consists of Lorentz-vector part j^®7> a n d scalar part l(x)l (and pseudoscalar part *y* ^ *j s* etc.[8])

This spin independent potential *U(r)* yields the following generalized Breit-Fermi potential for fine and hyperfine splittings,[4] »[9-13]

$$U_{\rm spin}=\frac{1}{3m_c^2}\left(\frac{{\rm d}^2V}{{\rm d}r^2}-\frac{1}{r}\frac{{\rm d}V}{{\rm d}r}\right)[\boldsymbol{s}_1\cdot\boldsymbol{s}_2$$
$$-3(\boldsymbol{s}_1\cdot\hat{r})(\boldsymbol{s}_2\cdot\hat{r})]+\frac{2}{3m_c^2}\boldsymbol{s}_1\cdot\boldsymbol{s}_2\nabla^2V(r)$$
$$+\frac{1}{2m_c^2r}\left(3\frac{{\rm d}V}{{\rm d}r}-\frac{{\rm d}S}{{\rm d}r}\right)(\boldsymbol{r}\times\boldsymbol{p})\cdot(\boldsymbol{s}_1+\boldsymbol{s}_2), \tag{2.4}$$

where *V* and *S* denote Lorentz-vector and scalar part[14] of *U(r),*

$$U(r)=V(r)+S(r),$$
$$V(r)=-\frac{4}{3}\frac{\alpha_s}{r}+far, \tag{2.5}$$
$$S(r)=(1-f)ar.$$

The contribution of pseudoscalar part, 7-5(8)7-5, due to multiple-gluon-exchanges to spin dependent potential is neglected for simplicity.

In order to explain the observed ^{3}***Pj*** splittings the fraction of Lorentz-vector vertices /V=l. For / = 1 , *lA^lMÇPJ-MÇPi)]/ [Mm-iMÇPoJl^Oà,*[10] while the experimental value of this ratio is about 0.42.

Quantitatively it is impossible to reproduce the hyperfine structure of the charmonium by this potential. The splitting of the *IS* states, M(l ^{3}5x)-M(l ^o), is found to be less than about 100 MeV, which should be compared with the experimental value, *M(J/<p)—M(X)=* 270 MeV.

One proposal to avoid this difficulty is to introduce an anomalous color "magnetic" term[12] *K* to the vector part of the linear confining potential *far.*[15-18] Then, the term *far* in the tensor and spin-spin interactions in (2.4) are multiplied by a factor (l+/r)^2 and that in the LS interaction is multiplied by a factor (1+**A**:). This hypothesis provides an extra parameter and can reproduce all of 1SV, *2Sj* and ^{3}***Pj*** splittings simultaneously[19] for /c=4~5, /«0.1 anda$_s$^0.45.

According to another proposal, instantons are responsible to the splitting of *Jj<p* and *rj$_c$*. Unfortunately there is no quantitatively reliable calculation of the contributions of instantons to the splitting. According to Wilczek and Zee,[20]

M(J/<p)-M($_{vc}$)~37r^{8}v^3/m^{2}c~450 MeV, (2.6)

where */u* is the usual renormalization scale and taken to be about 200 MeV. However, the numerical result is very sensitive to the cutoff in the size of the instantons.[21]

Next let us discuss electromagnetic transitions of the charmonium.

The El transition rates have been reproduced fairly well in the charmonium model.[22,23]

In the nonrelativistic quark model the Ml transition rates are expressed as[22,23]

$$\Gamma({\rm M1})=\frac{4}{3\pi}(2J_f+1)k^3\mu_c^2$$
$$\times|<f|-1+\frac{k^2r^2}{24}|i>|^2. \tag{2.7}$$

Therefore,

$$\Gamma_{\rm allowed}({\rm M1})=\frac{4}{3\pi}(2J_f+1)k^3\mu_c^2, \tag{2.8}$$

and

$$\Gamma_{\rm forbidden}({\rm M1})=\frac{1}{72\pi}\frac{k^7}{m_c^2\omega^2}(2J_f+1)\mu_c^2, \tag{2.9}$$

where *ix$_c$=e$_c$e%\2m$_c$c* and for simplicity we have used the wave factions of the harmonic oscillator potential in evaluating *{lS\r^2\2S}.*

If we identify X(2.83) with *y$_c$(l ^{x}S$_0$)* and %(3.45) with *r]'$_c$(2 ^{1}S$_0$),* we obtain the following predictions from (2.8) and (2.9),

$$\Gamma(J/\psi\to X\gamma)=29\ {\rm keV}\to Br(J/\psi\to X\gamma)=40\,\%, \tag{2.10a}$$

$$\Gamma(\psi'\to X\gamma)=8.5\ {\rm keV}\to Br(\psi'\to X\gamma)=4\,\%, \tag{2.10b}$$

$$\Gamma(\chi(3.45)\to J/\psi\gamma)=0.13\ {\rm keV}, \tag{2.10c}$$

$$\Gamma(\psi'\to\chi(3.45)\gamma)=21\ \text{keV}\to Br(\psi'\to\chi(3.45)\gamma)=9\%, \qquad (2.10d)$$

where /?z$_c$ = 1650MeV and <*>=330MeV determined from *M(<p')-M(J/<f>)* and $e^+e')=$ *\67ra^{2}el\(p(0)\$^2$/M(J/(py* are used. (See, Fig. 2.2.) All of these predictions are sources of troubles. Experimental results, *Br(J/(p-+ X$_r$)<U%* *Br(cp'-+X$_r$)<\%* and Br(«&'- X(3.45)F)<2.5%, are not compatible with the above theoretical values, and (2.10c) and the experimental results[24] *Br(x(3A5)-^J/(pr)>20%* predict *P$_r$(x(3A5))<0J* keV, which seems too small.

However, forbidden transition rates are not reliable since the matrix elements depend sensitively on the choice of the confining potential. For example, if we include spin-spin interaction in the unperturbed Hamiltonian, <1 *"S^ %>* and <1 *'S$_0$\2 ^{3}S$_1$)* are no longer zero and the forbidden Ml transition rates increases considerably.[23] There are also relativistic correction terms[25] </|2/?^{2}/3ra^2|/) + *(f\(S(r)/m$_c$)j$_0$(kr/2)\i}* to be added to the radial matrix element </|-l+(£V^2/24)|/>.

One proposed solution to the Ml troubles is as follows. *X(2.83)* and %(3.45) are not *rj$_c$* and *rj'$_c$*. Instead there are real *rj$_c$* and *rj'$_c$* with 100MeV>M(//^)-MO?$_c$)>0 and 50MeV> M(0')-AffoO^O. Then, what is Z(2.83) and #(3.45)? Lipkin has suggested[26] that *X* (2.83) are *ccqq* states *(q=u* and/or *d)* and that there are two 0$^+$ mesons, one with 7=0 and another with 7=1. He has also suggested that %(3.45) is a cess state with *J^P=0$^+$*. In order to test Lipkin's conjecture one should search for the transition *<p'-+Xp* since its observation indicates that *X* is not a cc state.

Now let me mention that the assignment of *X(2.83)* to *Y]$_c$* has another problem; If we use the formul a, *F(T]$_c$* -» 77)=48?ra V$_Q$ | *<p(0)* | 7 *M(r]y* and[27] *F(TJ$_c$* hadrons) » *F(rj$_c$ -> gg)=* (32^/3)a^2|0(O)|^2/M()7$_c$)^2, we find

$$Br(\eta_c\to\gamma\gamma)\approx 10^{-3}, \qquad (2.11)$$

while we obtain

$$Br(X\to\gamma\gamma)\gtrsim 0.008 \qquad (2.12)$$

from experimental results *Br(J\<p-*Xy)Br{X-* jj)={\A±0A)*x 10"^{4}and *Br(J/<p-*Xr)<*\.7%

The large branching ratio *Br (X-*]j)> 0.00%* indicates that hadronic decays of *X* are forbidden, for example, by flavor selection rules.

Finally let us discuss the candidate of a new charmonium level at 3.6 GeV observed in the *$'-+YjJI<p* decay and reported at this Conference.[3,28] If we identify this resonance with *rj'$_c$*, the allowed Ml transition rate is predicted to be

$$\Gamma(\psi'\to\chi(3.6)\gamma)=1.1\ \text{keV}\to Br(\psi'\to\chi(3.6)\gamma)=0.5\%, \qquad (2.13)$$

and the forbidden Ml transition rate is predicted to be

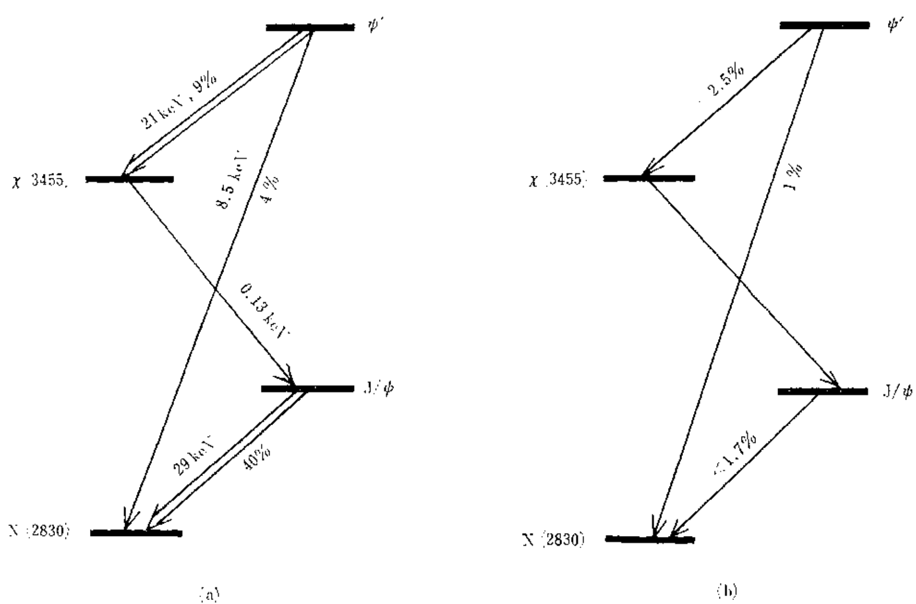

Fig. 2. 2. Ml transitions,
(a) Theory; (b) Experiment.

$$\Gamma(\chi(3.6)\to J/\psi\gamma)=10\ \text{keV}. \qquad (2.14)$$

Since experimentally[3]

$$Br(\psi'\to\chi(3.6)\gamma)Br(\chi(3.6)\to J/\psi\gamma)$$
$$=(2.8\pm1.2)\times10^{-3}, \qquad (2.15)$$

the branching ratio of the forbidden Ml transition is predicted to be

$$Br(\chi(3.6)\to J/\psi\gamma)\approx60\%, \qquad (2.16)$$

which is too large to be acceptable, it seems that the experimental result (2.15) is possible only if both radiative transitions are El transitions. This means that the spin-parity of the new resonance is 0^+, 1^+ or 2^+.

§3. r

Y was observed last summer as a strong enhancement at 9.5 GeV in the mass spectrum of dimuons produced in 400 GeV proton-nucleus collisions,[29]

$$\text{p}+(\text{Cu, Pt})\to\mu^++\mu^-+\text{anything},$$

at Fermilab. Later they found two peaks whose widths are consistent with their resolution and evidence for the possible existence of a third peak.[30]

Three months ago *Y* was confirmed by using the PLUTO and DASP detectors at DORIS in the reaction,[31]

$$e^++e^-\to\text{hadrons}.$$

According to their latest results [31]

$$M(\Upsilon)=9.46\pm0.01\ \text{GeV},$$
$$\Gamma_t(\Upsilon)>25\ \text{keV}\ (95\%\text{CL})$$
$$(\text{best value } 50\ \text{keV}),$$
$$\Gamma_{ee}(\Upsilon)=1.3\pm0.2\ \text{keV}.$$

At this Conference the confirmation of *Y'* at DORIS has been reported. According to their results,[3]

$$M(\Upsilon')-M(\Upsilon)\approx556\ \text{MeV},$$
$$\Gamma_{ee}(\Upsilon)/\Gamma_{ee}(\Upsilon')\approx3.$$

It is quite natural to regard the T-particle as a bound state of a new heavv quark and its antiparticle. While the existence of the charmed quark was predicted based on the lepton-hadron symmetry[32] and the absence of the strangeness changing weak neutral current,[33] a six-quark model was proposed by Kobayashi and Maskawa[34] in 1973 in order to explain CP nonconservation in the gauge model.[35] Properties of the six quarks, u, d, s, c, t and b, are summarized in Table I.

In Table I *T* and ***B*** are new quantum numbers conserved in both strong and electromagnetic interactions. The charges of hadrons are expressed as

$$Q=I_3+\frac{1}{2}(B+S+C+T+\boldsymbol{B}).$$

Let us determine the charge of the new heavy quark e_Q from the leptonic decay width of *Y* by making use of the nonrelativistic relation,[6]

$$\Gamma(V\to e^+e^-)=16\pi\alpha^2e_q^2|\psi_q(0)|^2/M_v^2, \qquad (3.1)$$

where |<^(0)| is the magnitude of the *qq* wave-function of the vector-meson *V dit* the origin.

From the leptonic decay widths of ***p**, **a),*** *<f>* and *Jjcp* Jackson derived an empirical formula,[22]

$$|\psi_q(0)|^2\propto M_v^{1.89\pm0.15}. \qquad (3.2)$$

Therefore, *r(V-*e+e~)/e²Q* should be nearly independent on the mass of the vector-meson[36] *M„* and we find

$$e_Q^2\approx\frac{1}{9}\ \text{but}\neq\frac{4}{9} \qquad (3.3)$$

as we can clearly see in Fig. 3. 1, in which *r(V^e+e~)le\ vs Ml* is plotted.

The conclusion (3.3) is also reached by comparing the lower bounds

$$\Gamma(\Upsilon\to e^+e^-)/e_Q^2>2.6\ \text{keV}$$

and (3.4)

r(X'^e+e')/e%>\A keV,

with the experimental results from DORIS. The lower bounds (3.4) were derived by Rosner, Quigg and Thacker[37] for potentials which are

Table I. Properties of six quarks.

Quark	Q	B	I	I_3	S	C	T	$\boldsymbol{B}$
u	2/3	1/3	1/2	1/2	0	0	0	0
d	−1/3	1/3	1/2	−1/2	0	0	0	0
s	−1/3	1/3	0	0	−1	0	0	0
c	2/3	1/3	0	0	0	1	0	0
t	2/3	1/3	0	0	0	0	1	0
b	−1/3	1/3	0	0	0	0	0	−1

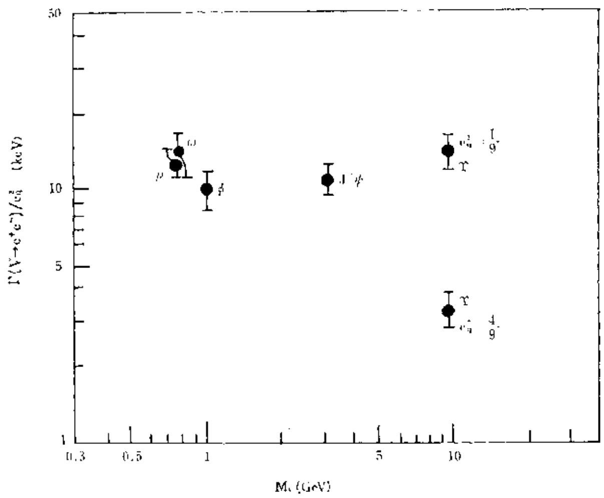

Fig. 3. 1. *r(V->e'e-)le'q vs Mv.*

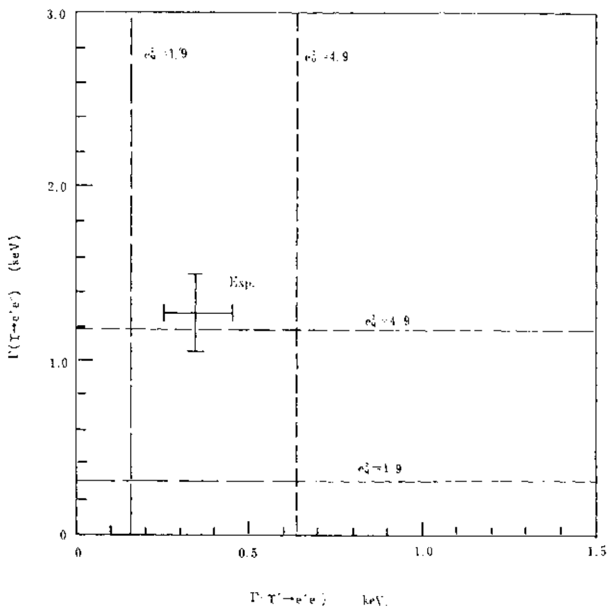

Fig. 3. 2. $\Gamma(\Upsilon\to e^+e^-)$ *vs* $\Gamma(\Upsilon'\to e^+e^-)$.

Lo\yer bounds on these leptonic decay widths for eQ**2**=4/9 and 1/9 are shown (broken lines). The observed value of *r(T-^e'e~)* is incompatible with the lower bound if *eQ²=4/9.* This figure is taken from ref. 37.

concave-downward, d²F/dr²<0. In deriving these lower bounds they have assumed that *mQ/mc>2.6* and made use of the experimental results *r(J/<p-+e'e-)=(4.S±0.6)* keV and *r(<p'->e'e~)=(2A±03)keV.* We find that the experimental value of *rÇY'~*e+e~)* is incompatible with the lower bound (3.4) in the case of 4=4/9. (See Fig. 3.2.)

Of course, the best way to prove that *Y* is a bound state of *b* and *b* is to find an isodoublet of "beautiful" ("bottom") mesons, *B°=(bd)* and *B~=(bu).*

The dominant decay modes of these mesons involve charmed mesons,

5°, 2?~-»a charmed meson+wr.

Last year several papers on the bound states of a new heavy quark and its antiparticle were published. For example, before the discovery of *Y* Eichten and Gottfried[38] calculated the energy levels to be expected from the potential model used in charmonium. Their potential

$$U(r)=-\frac{4}{3}\alpha_s(m_c^2)/r+r/a^2 \qquad (3.5)$$

(as(ra²)=0.19 and a=2.22GeV"¹) predicts M(**r**')-M(**r**)-420MeV, which should be compared with the experimental result, 556 MeV.

The difference of the predicted and experimental level spacing *M(Y')—M(Y)* suggests that the shape of the above potential must be modified, and it has been noticed[39] that the apparent equal spacing,

$$M(\Upsilon')-M(\Upsilon)\approx M(\psi')-M(J/\psi);\ 556\ \text{MeV}$$

vs 588 MeV, is realized in the nonrelativistic limit if a logarithmic potential[40]

$$U(r)=C\ln(r/r_0),\quad C\approx 0.75 \qquad (3.6)$$

is used instead of (3.5).

Though £/(r)=C In (r/r₀) is unique in giving level spacing independent of the quark mass, the equal spacing, *M(Y')-M(Y)^M(<p')-M(J/(p),* is reproduced by the modified Coulomb Dotential[39,41]

$$U(r)=-\frac{4}{3}\alpha_s/r+r/a^2 \qquad (3.7)$$

with as^0.45 and a=2.48 GeV⁻¹. It is interesting to notice that the value *aszzOA5* is the value used in order to reproduce the *IS, 2S* and *³Pj* splittings of charmonium.

Now let us consider the magnitude of the quark-gluon fine structure constant, *as(q²).* In QCD

$$\alpha_s(q^2)\approx[12\pi/(33-2F)]/\ln(q^2/\Lambda^2), \qquad (3.8)$$

where *F* is the number of quark flavors. Various experimental data, *e.g.,* scaling violations in deep inelastic reaction indicates[42] 4=0.3~0.7 GeV. If we use (3.8) with 4=0.5 GeV, we find *as(ml)==0.63;* and if we choose *A=* 0.3 GeV, we find *as(ml)=0M.* These results are by a factor of three or two bigger than the value as(m²)=0.19 obtained at time-like *q²^— m²c.*

However, we have to notice that the running constant $a_s(q^2)$ evaluated at time-like $q^2=-m_c^2$ and that evaluated at space-like $q^2=m_c^2$ are different in general since q^2 is finite.[43]

Now let us discuss one-gluon-exchange potential. Because of the q^2 dependence of a_s, which is expressed in (3.8), the l/r behavior of the Coulomb type potential is modulated by an inverse log factor. The asymptotic form of the Fourier transform of $oc_s(q^2)jq^2$ as $r\to+0$ is given by[44]

$$[87r/(33-2F)]/(r\ln r). \quad (3.9)$$

However, traditionally this effect has been ignored by taking an average value of a_s at $q^2=m_c^2$. I consider that it is more appropriate to evaluate a_s at $q^2=(l/r)^2$. The average of l/r, $(\backslash r\}\wedge(kM)^{1/(2+X)}$ for power-law confining potential $U(r)=kr^x/A_9$ where M is the reduced mass of the system. For the charmonium in the harmonic oscillator potential <l/r> ^0.6 GeV.

Of course we can use the Fourier transform of $a_s(q^2)/q^2$ as the one-gluon-exchange potential.[44,45]

Next let us discuss the hadronic decay width of T. According to QCD,[5]

$$\Gamma_h(\Upsilon)\approx\Gamma(\Upsilon\to ggg)$$
$$=(160/81)(\pi^2-9)(\alpha_s^3/M(\Upsilon)^2)|\psi(0)|^2 \quad (3.10)$$

and[6]

$$\Gamma_{ee}(\Upsilon)=16\pi\alpha^2e_b^2|\psi(0)|^2/M(\Upsilon)^2. \quad (3.11)$$

Therefore.

$$\Gamma_h(\Upsilon)/\Gamma_{ee}(\Upsilon)\approx(10/81\pi)(\pi^2-9)(\alpha_s^3/\alpha^2e_b^2)$$
$$=19.5 \quad (3.12)$$

for $\#_s=0.15$, which is derived from

$$\alpha_s(s)=\alpha_s(\mu^2)[1+(23/12\pi)\alpha_s(\mu^2)\ln(s/\mu^2)]^{-1}, \quad (3.13)$$

and a,=0.19 for $J/<p$. In (3.12) e_b stands for the charge of the b-quark.

The QCD prediction (3.12) seems somewhat smaller than the experimental result,[3]

$$r_h(r)/r_{ee}(T)=(>25 \text{ keV; best value 50 keV}) \times(1.3\pm0.2\text{keV})^{-1}. \quad (3.14)$$

But, they are compatible if we make a correction for second order electromagnetic decays to the hadronic decay width of *T*.

There is an inequality on the mass of the b-quark,

$$m_b-m_c>3.29\text{GeV} \quad (3.15)$$

derived by Grosse and Martin[46] for potentials which satisfy the conditions,

$$-\infty<\lim_{r\to\infty}[rV(r)]\leq0$$

and (3.16)

$$(\wedge)\mathbf{Wo}-)]>o$$

and by making use oi the experimental values of the masses of T, *T'* and *J/(p.*

§4. Spectroscopy of Old Hadrons and QCD

Effective quark-quark interaction suggested by QCD, which has been applied to charmonium and *T* in the previous sections has been applied to the spectroscopy of old hadrons.

A long-range Lorentz-scalar confining force, together with a short-range Coulomb-like vector exchange has been applied to meson spectroscopy by Schnitzer.[18] This interaction gives an excellent overall account of the spin structure of ordinary mesons, if $a_s(M^2)$ is sufficiently large as has been suggested by the violation of scaling in deep inelastic processes,

$$\alpha_s(M^2)=(12\pi/25)(\ln M^2/\Lambda^2)^{-1}$$

with $A=0.5$ GeV. Here, M is taken to be the mass of the bound state.

This model predicts the inverted **P* multiplets for *D* and *F* charmed mesons and bottom mesons,[1*,47]

$$M(^3P_0)>M(^3P_1)>M(^3P_2).$$

The hyperfine interaction arising from a short-range Coulomb-like vector exchange with $a_s\sim l$ together with flavor independent long-range confining force has been applied to the spectrum and mixing angles of baryons by Isgur and Karl.[48,49] They have found a good agreement in the $S=0$ and $S=-l$ sector (except for 4(1405) /^{p}=1/2-). They have discarded the spin-orbit interaction from the vector-exchange since they may be cancelled by the spin-orbit interaction from the long-range Lorentz-scalar confining force.

§5. Charmed Hadrons

The observation of the *D* and *Z>** mesons were reported at the last conference. Last year candidates of the *F* and *F** mesons have been discovered at DESY with the following masses[50,3]

M(/0=(2.03±0.06) GeV

and (5.1)

$$M(F^*)-M(F)=(110\pm46)\ \mathrm{MeV}.$$

Some branching ratios of the *D* mesons have been measured. The observed branching ratio of the inclusive semileptonic decay is[51]

$$Br(D\to e\nu X)\approx 10\%. \tag{5.2}$$

If the nonleptonic decays of the D-mesons are not enhanced, we expect

$$Br(D\to e\nu X)\approx 20\%. \tag{5.3}$$

Thus the nonleptonic decays of the D-mesons are enhanced by a factor of about 8/3. Therefore, we do not have a serious problem such as the origin of the |J/|=l/2 rule in the hyperon decays and 7£-meson decays. In these decays \Al\=\j2 part is enhanced by a factor of about 20.

Main part of the difference between (5.2) and (5.3) may be explained by QCD, in which nonleptonic decays are enhanced by a factor,[52]

$$(2c_+^2+c_-^2)/3\approx 5/3, \tag{5.4}$$

and semileptonic decays are suppressed as much as 35 %,[53] where

$$c_-=\{1+[(33-2F)/12\pi]\alpha_s(m_c^2)\times\ln(m_W^2/m_c^2)\}^{12/(33-2F)}$$

and (5.5)

$$c_+=(c_-)^{-1/2}.$$

In (5.4) we have used $c_-=2.0$ and $c_+=0.7$ assuming $\alpha_s(m_c^2)=0.7$.

Because of the large masses, the charmed mesons decay into various channels and through the study of these decays we can test various models of weak nonleptonic decays. For example, by making use of the bounds[54]

$$0<\Gamma(D^+)/\Gamma(D^0)<3, \tag{5.6}$$

which are imposed by the |J/|=1 rule, and the measured branching ratios of D⁺~»K~7r⁺7r⁺ and J5°-^K"7r⁺7r°,[55] it has been shown that the matrix elements of some of *D-^Kn7t* decays cannot be uniform over the Dalitz plot[56]""[59]. It has been suggested that *D'K~'7t'x⁰* decay is dominated by *K~p⁺* states.[57]

§6. *v*

All observed properties of r are consistent with those of a new sequential heavy lepton.[61,60] (See, Table II.)

Table II. r decays

Decay mode	Experiment	Theory[61]
$e\nu\bar\nu$	16.9±1.9%	~18%
$\mu\nu\bar\nu$	18.3±1.9%	~18%
$\pi\nu$	7.7±1.3%	~10%
$\rho\nu$	24 ±9 %	~22%

If *T* is a bound state of a b-quark and its antiparticle, and if the b-quark and the t-quark belong to a doublet of the weak SU(2) group, we find a beautiful correspondence between

(w, d), *(c, s)* and *(t, b),*

and

(e, ν_e), *(p,* and (r, ν_τ).

§7. **Baryonium**

In the nonrelativistic quark model a baryon is a bound state of three quarks, and a meson is a bound state of a quark and an antiquark.

However, there are some indications that there might be other types of mesons.

For example, several narrow peaks have been observed in *pp* system[3]

Name	Mass (MeV)	Width (MeV)	Remarks
S	1936±1	< 4~8	$\bar{p}p$ formation experiment,[62]
—	2020±3	≲10~20	baryon exchange reaction,[63]
—	2204±5	≲10~20	

Here S(1936) is a narrow resonance with a large elasticity. There are additional indications of narrow resonances with i?=0.[64]

It is difficult to regard the narrow resonances observed *IN PP* system, such as S(1936), as mesons which consist of a quark and an antiquark. These resonances have narrow widths of about 10 MeV in spite of their high masses. They are characterized by their reluctance for decaying into meson states, as inferred either from the measured branching ratios, or from their small total widths. That is, their couplings with mesons are weak. Therefore, they are popularly called "baryonium/[565]

Necessity of such resonances was advocated by Rosner when duality was applied to baryon-antibaryon reactions[66,67] In order to draw duality diagrams for *BB-+BB* we have to introduce resonances which consist of two quarks and two antiquarks *iqqqq)* (Fig. 7.1). If the *qqqq* resonances couple strongly with

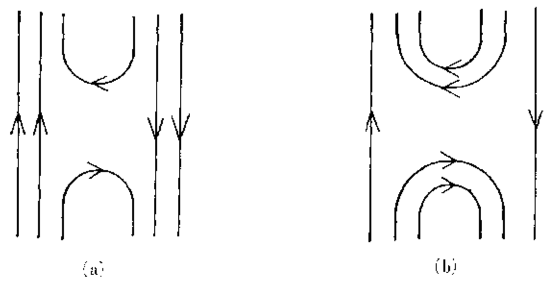

Fig. 7. 1. Duality diagrams for $B\bar{B}\to B\bar{B}$.

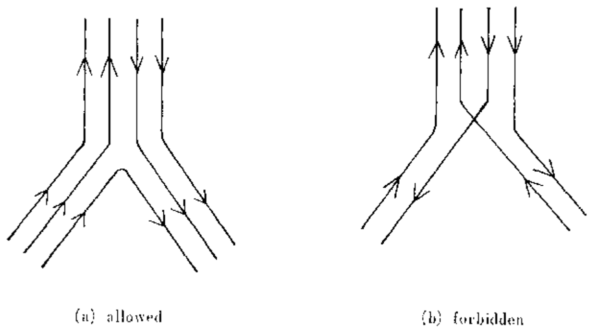

Fig. 7. 2. Freund-Waltz-Rosner rules,
(a) allowed; (b) forbidden.

two-meson states, we cannot expect that the vector and tensor trajectories are exchange degenerate. Therefore, the *qqqq* resonances are not allowed to couple strongly with meson states in dual models.

Thus, the following selection rules for the vertices were proposed by Freund, Waltz and Rosner[68];

(1) Every quark-line connects two different hadrons. (OZI rule)

(2) Every pair of the hadrons must be connected by at least one quark-line.

According to these rules, the decays of the *qqqq* resonance into *BB* states are allowed but the decays into meson states are forbidden. (See Fig. 7.2.)

If the baryonium is a *qqqq* resonance, we have to explain how two quarks and two antiquarks are bound together and why it cannot decay into mesons strongly. In order to answer these questions we have to know how a quark-antiquark pair and three quarks are confined to the interior of mesons and baryons, respectively.

There are several models of hadrons. As examples let us consider the junction model[69-71] and the bag model.[72-74]

7.7 *Exotic mesons in the junction model*

In the junction model mesons are bound states of a colored quark and a colored antiquark bound by a colored oriented string (Fig. 7.3 (a)). Baryons consist of three colored quarks, each of which is tied at the end of three colored oriented strings, and the three strings are joined at a point called the string "junction"[69,70] (Fig. 7.3(b)).[75,76]

The meson and baryon in this model shown in Fig. 7.3 correspond to the following color gauge invariant operators,[71]

$$\bar{\psi}^i(x)[G(P(x,y))]_i^j\psi_j(y) \tag{7.1}$$

and

e*»[G(P(x, y)W(yMG(P(x, z))^(z)],
X [% w M 4 (7.2)

respectively, where

$$[G(P(x,y))]_i^j=\left[T\exp\int_{P(x,y)}A_\mu(x)\mathrm{d}x^\mu\right]_i^j, \tag{7.3}$$

and *ij* and *k* are color SU(3) indices.

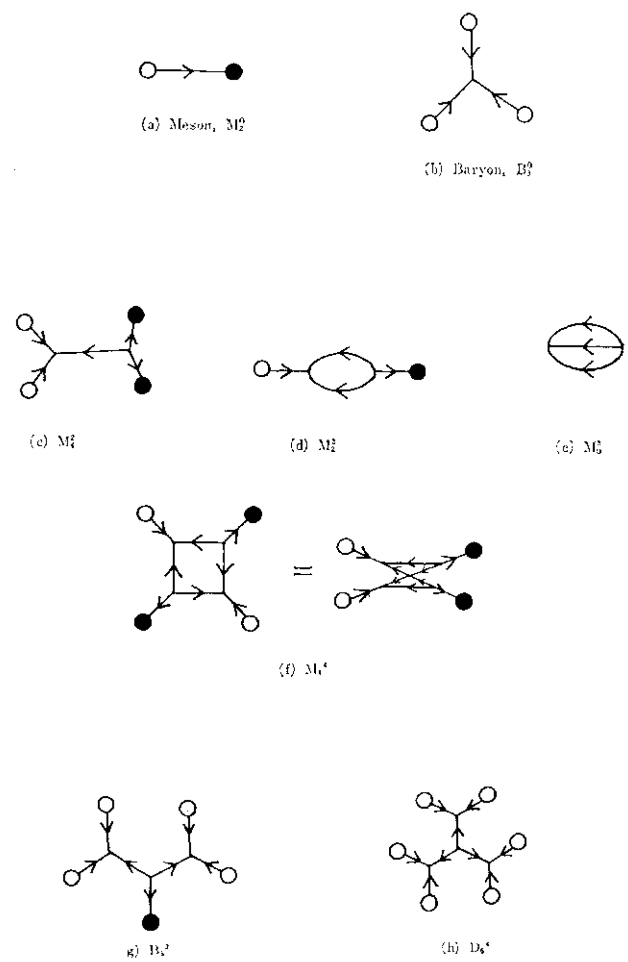

Fig. 7. 3. Various types of hadrons in the junction model.
(a) Meson, M_2^0; (b) Baryon, B_3^0; (c) M_4^2; (d) M_2^2; (e) M_0^2; (f) M_4^4; (g) B_5^3; (h) D_6^4.

In the junction model baryons consist of three colored quarks (tied at the ends of three strings) and a junction. Hence, we draw junction lines (broken lines) as well as quark lines (solid lines) in duality diagrams.

Various hadrons of new types can be constructed of quarks and junctions. In Fig. 7.3 some of possible types of hadrons in this model, *Ml Ml Ml Mi Bl* and *D* are also shown. Here, the superscripts are the numbers of the junctions, N_{j}, and the subscripts are the numbers of the quarks and antiquarks, N_q.

Since hadrons are regarded to consist of quarks and junctions, Freund-Waltz-Rosner rules for vertices are enlarged as follows[77]:

(1) Every quark-line and every junction-line connect two different hadrons.

(2) Every pair of hadrons must be connected by at least one quark-line or one junction-line.

These rules are called covalence rules by Imachi and Otsuki.[77]

Then, the following decays into meson states are forbidden by the rules (1) and/or (2), (Fig. 7.4)

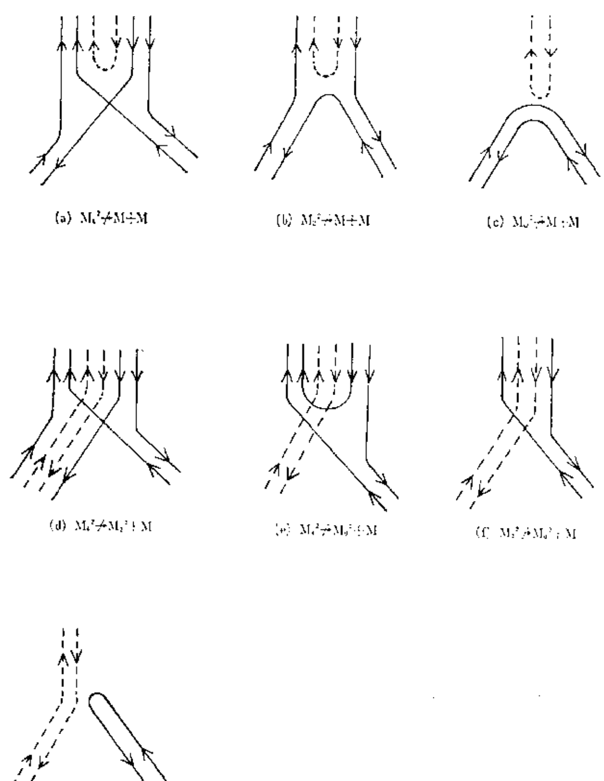

Fig. 7. 4. Forbidden decays of baryonium.
(a) $M_4{}^2 \not\to M+M$; (b) $M_2{}^2 \not\to M+M$; (c) $M_0{}^2 \not\to M+M$; (d) $M_4{}^2 \not\to M_2{}^2+M$; (e) $M_4{}^2 \not\to M_0{}^2+M$; (f) $M_2{}^2 \not\to M_0{}^2+M$; (g) $M_0{}^2 \not\to M_0{}^2+M$.

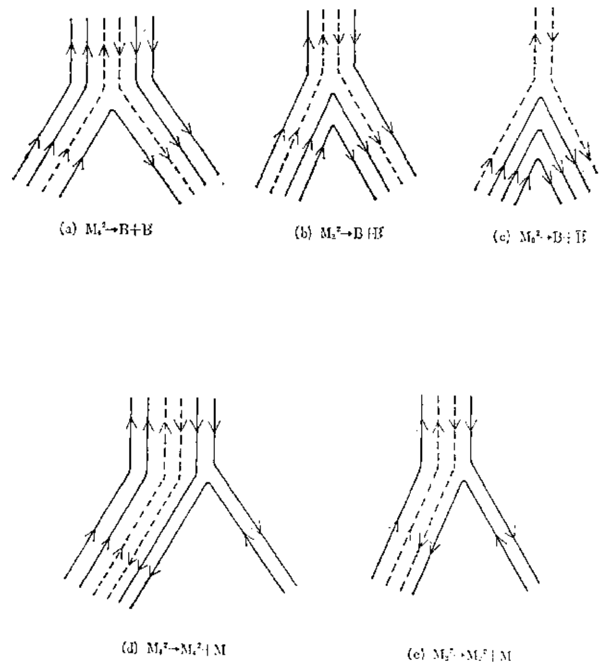

Fig. 7. 5. Allowed decays of baryonium.
(a) $M_4{}^2 \to B+\bar{B}$; (b) $M_2{}^2 \to B+\bar{B}$; (c) $M_0{}^2 \to B+\bar{B}$; (d) $M_4{}^2 \to M_4{}^2+M$; (e) $M_2{}^2 \to M_2{}^2+M$.

$$M_4^2 \not\to MM,\ M_2^2 \not\to MM,\ M_0^2 \not\to MM,$$
$$M_4^2 \not\to M_2^2 M,\ M_4^2 \not\to M_0^2 M,\ M_2^2 \not\to M_0^2 M,$$
$$M_0^2 \not\to M_0^2 M, \tag{7.4}$$

but the following decays into *BB* states are allowed, (Fig. 7.5)

$$M_4^2 \to B\bar{B},\ M_2^2 \to B\bar{B},\ M_0^2 \to B\bar{B}. \tag{7.5a}$$

Therefore, we may call *M*, *M* and *Ml* baryonium. The mesonic decays of baryonium, *M* and *Ml*, into the baryonium of the same type are also allowed, (Fig. 7.5).

$$M_4^2 \to M_4^2 M,\ M_2^2 \to M_2^2 M. \tag{7.5b}$$

The allowed decays of baryonium occur through string breaking and fusion of "active" quarks created by the breaking.

There are several attempts to justify the covalence rules from the exchange degeneracies of baryons.[75,78,79]

In Fig. 7.6 we show some of the duality diagrams in this model. From the duality diagrams, we find that the Regge trajectories *a%'q* of the baryonium *M%'q9* *a\(s), a\(s)* and *a\{s)* are dual with ordinary meson trajectory $a_M(s)(=a(s))$, two-meson *(MM)* cut and three-meson *(MMM)* cut, respectively. The effective slopes of MM-cut and *MMM-cut* are *(l/2)a'* and (1/3)a', respectively. Therefore, we obtain

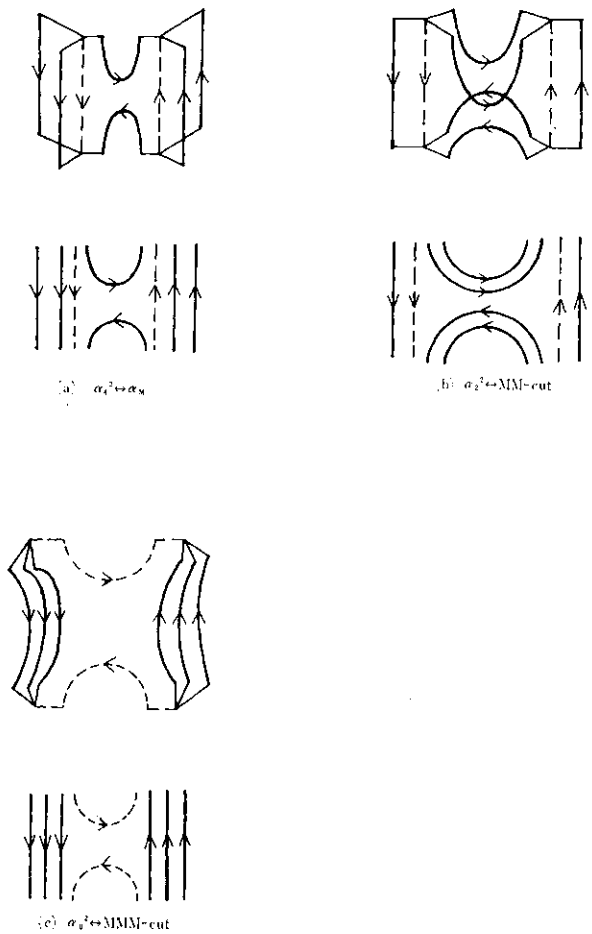

Fig. 7. 6. Duality diagrams in the junction model. (a) $\alpha_4{}^2\leftrightarrow\alpha_M$; (b) $\alpha_2{}^2\leftrightarrow MM$-cut; (c) $\alpha_0{}^2\leftrightarrow MMM$-cut.

$$\alpha_4^{2\prime}\approx\alpha',\ \alpha_2^{2\prime}\approx(1/2)\alpha',\ \text{and}\ \alpha_0^{2\prime}\approx(1/3)\alpha' \tag{7.6}$$

from semilocal duality.[7179]

According to the dual unitarization scheme,[80] we find the following rule for the zero-intercepts,[81]

$$\alpha_{N_q}^{N_J}(0)\approx1-(1/4)N_q-(1/4)N_J-(1/4)N_s, \tag{7.7}$$

where N_s is the total number of .y-quark and >quark.

Therefore, assuming linear trajectories for the baryonium, we obtain

$$\begin{aligned}\alpha_4^2(s)&\approx-0.5+\alpha' s,\\ \alpha_2^2(s)&\approx(1/2)\alpha' s,\\ \alpha_0^2(s)&\approx0.5+(1/3)\alpha' s.\end{aligned} \tag{7.8}$$

(See, Fig. 7.7.)

I will not try to assign observed narrow resonances to some of M[2] states in this talk.[79].[82] Of course, it is possible to assign some of them to ***Ml**-***[8']

7.2 qqqq states in the bag model

In the bag model colored quarks and antiquarks are confined to the interior of a finite domain called a bag. In this model long-range confining forces are replaced by thé bag pressure, *B.* There are the following contributions to a hadron mass in the model[72-74]; 1) the quark mass and kinetic energy; 2) the energy stored in the confining forces (bag energy); 3) the finite energy associated with zero-point energies of the fields confined to the bag; (We have to include this energy since it is dependent on the radius of the bag, *R.)*\ and 4) the spin-spin interaction arising from one-gluon exchange;

$$M=\sum_i\frac{\alpha_i(R)}{R}+\frac{4\pi}{3}R^3B-\frac{Z_0}{R}+\sum_{ij}V_{ij}(R). \tag{7.9}$$

The bag model has been successful in describing the spectrum of light hadrons (l/2⁺ and 3/2⁺ baryons, 0~ and 1~ mesons),[74] and car be applied to *qqqq* states without introducing new parameters.[85] In the bag model L=C *qqqq* states are constructed by populating quark modes in a bag. Jaffe and Johnson[85] found the lowest mass *qqqq* states to be an SU(3) nonet of scalar mesons with masses ranging from 645 to 1120 MeV,

$$\begin{aligned}
&E_K^+;\ ud\bar{s}\bar{d},\ E_K^0;\ ud\bar{s}\bar{u}, && \sim\ 880\ \text{MeV},\\
&E_{\bar K}^0;\ us\bar{u}\bar{d},\ E_{\bar K}^-;\ ds\bar{u}\bar{d}, && \sim\ 880\ \text{MeV},\\
&E^+;\ us\bar{d}\bar{s},\ E^0;\ (us\bar{u}\bar{s}\text{-}ds\bar{d}\bar{s})/\sqrt{2},\\
&E^-;\ ds\bar{u}\bar{s}, && \sim1120\ \text{MeV},\\
&E_2^0;\ (us\bar{u}\bar{s}+ds\bar{d}\bar{s})/\sqrt{2}, && \sim1120\ \text{MeV},\\
&E_1^0;\ ud\bar{u}\bar{d}, && \sim\ 645\ \text{MeV},
\end{aligned}$$

by making use of the parameters used in describing the spectrum of the light hadrons.

They have suggested that the scalar nonet [e(700)?, S*(993), 3(980), 4800-1100) ?][86] should be identified with the above scalar *qqqq* nonet than with the $^3P_0$ nonet of the conventional nonrelativistic quark model.

In the bag model *L=0 qqqq* states are expected to be broad. A broad *qqqq* state can simply fall apart into two *qq* mesons.

Higher orbital angular momentum states are obtained by rotating the bag with a diquark in one side and an antidiquark in another side of an elongate bag. There are two quark configurations.[87] In one con-

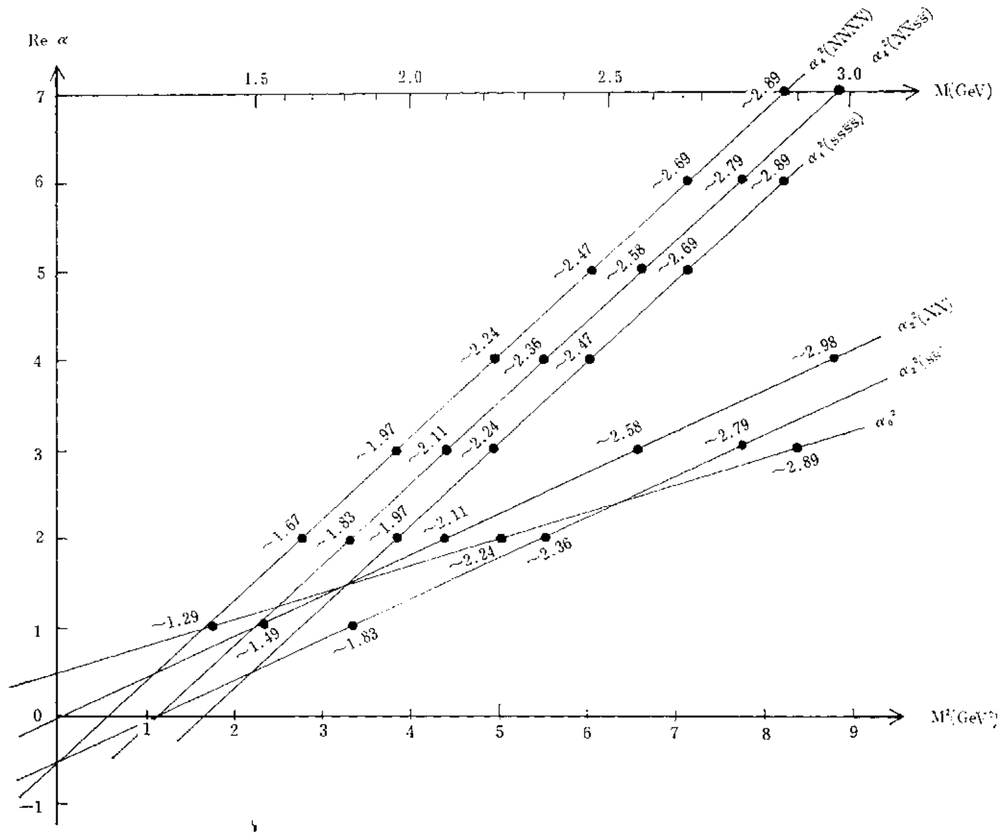

Fig. 7. 7. Regge trajectories of baryonium (for $\alpha'=0.9$ GeV^{-2}).
Here, leading trajectories $\alpha_4{}^2\,(NN\bar{N}\bar{N})$, $\alpha_4{}^2\,(N\bar{N}s\bar{s})$, $\alpha_4{}^2\,(ss\bar{s}\bar{s})$, $\alpha_2{}^2\,(N\bar{N})$, $\alpha_2{}^2\,(s\bar{s})$ and $\alpha_0{}^2$ are shown, where N stands for u and/or d.

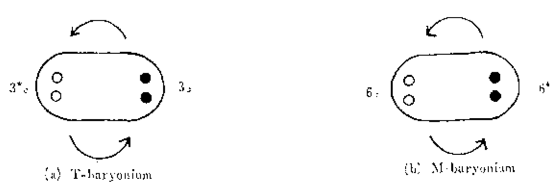

Fig. 7. 8. *qqqq* states with high spin in the bag model.
(a) T-baryonium; (b) M-baryonium.

figuration both the diquark and the antidiquark are color-triplets (T-baryonium) and in another configuration both are color-sextets (M-baryonium),[88] *i. e.*,

$$(qq)_{3^*}-(\bar{q}\bar{q})_3, \qquad \text{(T-baryonium)}$$

and

$$(qq)_6-(\bar{q}\bar{q})_{6^*}, \qquad \text{(M-baryonium).}$$

(Fig. 7.8)

Two types of the *qqqq* states lie on Regge trajectories with different slopes. Let us discuss the slopes of the Regge trajectories. Asymptotically for large mass, we expect the trajectories to be linear in M^2. In the bag model the slope is proportional to $(\hat{o}^2)^{\sim 1/2}$, where Q^2 is the quadratic Casimir for the color SU(3) representation inside the bag,[89]

$$Q^2=16/3 \quad \text{for } 3,$$
$$=40/3 \quad \text{for } 6. \qquad (7.10)$$

Therefore, the T-baryonium slope a'_T is the same as that for ordinary *qq* mesons,

$$\alpha'_T=\alpha'\approx 1\ \text{GeV}^{-2} \qquad (7.11a)$$

and the M-baryonium slope is given by

$$\alpha'_M=\sqrt{2/5}\,\alpha'_T\approx 0.63\ \text{GeV}^{-2}. \qquad (7.11b)$$

The T-baryonium and M-baryonium have very different physical properties.[88] Although both are expected to have inhibited decays into pions because of the angular momentum barrier, they have different couplings to *BB*. The diquark in a T-baryonium state, being in a 3^representation, can combine with another quark in a 3 representation to form a color singlet baryon. (Fig. 7.9(a).) Therefore, the T-baryonium couples strongly with *BB* channel and is expected to have a decay width of ~ 100 MeV. Whereas M-baryonium[90] cannot decay in this manner, since the diquark in a 6-representation when combined with another quark in 3 does not give a color singlet ($6\times 3=10+8$). They are, therefore, weakly coupled both to meson and *BB* channels (Fig. 7.9(b)-(e)), and prefer to decay by cascade into a

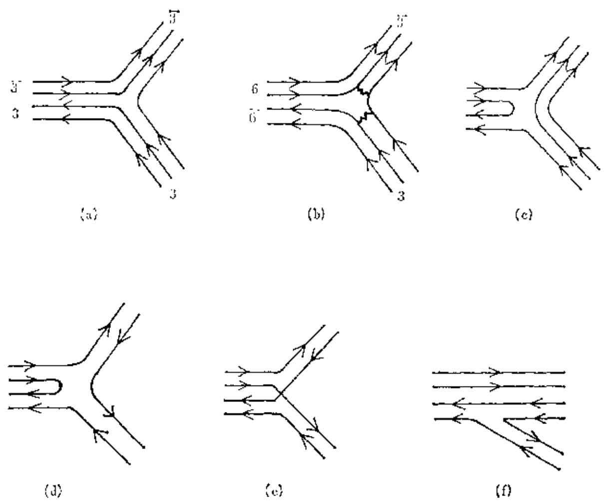

Fig. 7. 9. Decays of T-baryonium and M-baryonium

resonance of the same type[88] (Fig. 7.9(f)).

Observed narrow resonances have been assigned to baryonium states by Chan and Hogaasen.[88,84]

Finally let us discuss the stability of the baryonium.[91]

The mass of T- and M-baryonium have been estimated by Barbour and Ponting[92] in variational method by making use of a model Hamilton ian. According to their results, in the T-baryonium case the two ##-meson states, through which baryonium may decay into meson final states, are generally found to be more massive than the baryonium state itself, but in the M-baryonium case they are lighter than the baryonium state.

However, asymptotically for large mass, the M-baryonium with spin *J* is lighter than the two g ^-mesons with spin *J/2* since[93] *2a'*$_M$> ***a';*** Since the mass *(M)* of the M-baryonium with spin / is « ***jjfâ****=(j5j2J/ay*^{2} *(/~ a'*$_M$*M*^{2}*)* and since the mass (m) of the *qq*-meson with spin *J/2* is ***œ</j****/2a' (J/2~a'm*^{2}*),* *2m « V2J/****a****'>* (5/2)$^{1/4}$ ***VJJa***'^ *M.* Notice, however, this argument is applicable only when |or(**0**)|</.

§8. Dibaryons

Once pp total cross sections were considered to be roughly energy independent.[94] If they are independent of energy, there should be no hadrons with baryon number two in dual models.

Recently a remarkable energy dependence has been discovered in measurements of pp total cross sections with a polarized beam and target,[95] and several evidences on the existence of the hadrons with baryon number two listed in Table III have been reported.[95-101]

5^2(2.14) and *B\2.22)* are characterized by their small elasticity.

The deuteron is not listed in the table since it is not a hadron, but a nucleus, *i. e.,* a bound state of a proton and a neutron bound by nuclear force. To regard the deuteron as a six-quark state is not adequate.[103] In the terminology of the quark model it is a molecular state of two clusters of three-quarks bound by colorless interaction.

Then, are 5^2(2.14) and 5^2(2.22) the subject of this conference, /. e., are they nuclei or hadrons? I would like to regard them as hadrons because of their small elasticity and their small sizes.

The bag model has been applied to dibaryon resonances.[104,105] In the bag model *L=0* six-quark states are constructed by populating quark levels in a bag. The predicted energy levels are

$$I=1;\ {}^1S_0\ (M=2.24\ \text{GeV}),\quad {}^1D_2\ (M=2.36\ \text{GeV})$$

$$I=0;\ {}^3S_1\ (M=2.16\ \text{GeV}),\quad {}^3D_3\ (M=2.36\ \text{GeV}).$$

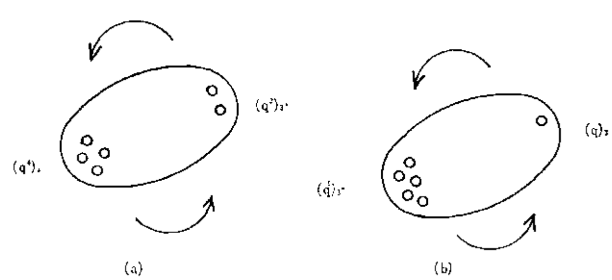

Fig. 8. **1.** Dibaryon resonances in the bag model a*o)..

Table III. Dibaryon resonances.

Name[102]	Mass (GeV)	Width (MeV)	I	NN-state	Elasticity	Remarks
B^2 (2.14)	2.14–2.17	50–100	1	$^1D_2$	0.1	$\Delta\sigma_L$, $\Delta\sigma_T$ etc.[95~98]
B^2 (2.22)	2.20–2.26	100–150	1	$^3F_3$	0.2	$\Delta\sigma_L$ etc.[95,96,99]
B^2 (2.43)	2.43–2.50	150	1	$^1S_0$ or $^1G_4$		$\Delta\sigma_L$, $\Delta\sigma_T$, C_{LL} etc.[95]
B^2 (2.38)	2.38	?	0?	?		γd→np↑[100,101]

L=l negative parity resonances are obtained by rotating the bags with the following clusters of quarks in two ends,

$$(q^4)_3-(q^2)_{3^*},\ (q^5)_{3^*}-(q)_3 \text{ etc.}$$

(See, Fig. 8.1.) Mulders, Aerts and de Swart have estimated the masses of dibaryon states in the bag model.[105] Some states occur with quantum numbers foreign to NN states, which they refer to as extraneous states.

§9. Concluding Remarks

Any talk on particle spectroscopy is incomplete unless something is mentioned about the quarks.

An expert on English literature told me that there were four seagulls in a dence fog when Tristan and Isolde heard three quarks.[106]

Now we have already found five seagulls and it seems that there is at least one more seagull in a fog. Let me speculate that this sixth seagull will be discovered before next Conference.

Acknowledgments

I would like to thank Dr. T. Kobayashi, Dr. S. Sakai, Dr. T. Inami, Prof. Y. Iwasaki, Prof. H. Miyazawa and Prof. M. Uehara for fruitful discussion. I would like to express my sincere gratitude to Prof. J. D. Jackson for his valuable advices and comments. It is a great pleasure to acknowledge the help I have received from Prof. J. Arafune, the scientific secretary.

References

1. **H.** Yukawa: Proc. Phys.-Math. Soc. Japan, **17** (1934) 48.
2. G. Feldman and M. L. Perl: Phys. Reports, **33** (1977) 285.
3. G. Flugge: rapporteur talk at this Conference.
4. A. DeRûjula, H. Georgi and S. L. Glashow: Phys. Rev. **D 1 2** (1975) 147.
5. T. Appelquist and H. D. Politzer: Phys. Rev. Letters **34** (1975) 43; Phys. Rev. **D 1 2** (1975) 1404.
6. R. Van Royen and V. F. Weisskopf : Nuovo Cimento, 50A (1967) 617.
7) E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane and T. M. Yan: Phys. Rev. Letters **34** (1975) 369.
8. The contributions from multiple-gluon-exchange to *OfâOi* with *i=P*, *T* and *A* have no spin independent component in the static limit.
9. J. Pumplin, W. Repko and A. Sato: Phys. Rev. Letters **35** (1975) 1538.
10. H. J. Schnitzer: Phys. Rev. Letters **35** (1975) 1540.
11. H. J. Schnitzer: Phys. Rev. **D 1 3** (1976) 74.
12. H. J. Schnitzer: Phys. Letters **6 5 B** (1976) 239.
13. See, also, J. S. Kang and H.J. Schnitzer: Phys. Rev. **D 1 2** (1975) 841 ; J. G. Wills, D. B. Lichtenberg and J. T. Kiehl: Phys. Rev. **D 1 5** (1977) 3358 ; K. Hirata, T. Kobayashi and N. Nakamaru: Phys. Rev. **D 1 8** (1978) 834; W. Celemaster, H. Georgi and M. Machacek: HUTP-771A051; D. B. Lichtenberg and J. G. Wills: IUHET-27.
14. A. B. Henriques, B. H. Kellett and R. G. Moorhouse: Phys. Letters **6 4 B** (1976) 85.
15. X. Y. Pham and J. M. Richards: Phys. Letters **70B**(1977) 370.
16. L. H. Chan: Phys. Letters **7 1 B** (1977) 422, Paper No. 6 submitted to this Conference.
17. C E . Carlson and F. Gross: Phys. Letters **7 4 B** (1978) 404.
18. H.J. Schnitzer: Paper No. 46 submitted to this Conference.
19. In this model

$$M(^3S_1)-M(^1S_0)=\frac{32\pi}{9m_c^2}\alpha_s|\phi(0)|^2 + \frac{4}{3}\frac{fa(1+\kappa)^2}{m_c^2}\langle r^{-1}\rangle_{\text{S-wave}}.$$

20. F. Wilczek and A. Zee: Phys. Rev. Letters **40** (1978) 83.
21. See, also, M. Suzuki: Phys. Letters **7 6 B** (1978) 466; C. G. Callan, R. Dashen, D.J. Gross, F. Wilczek and A. Zee: Princeton preprint, COO-2220-132; According to Suzuki (private communication), *V_ss(0)<36MeV SX'S₂*.
22. J. D. Jackson: *Proc. Summer Inst. Particle Physics* SLAC Report No. 198 (1976) p. 147.
23. J. Arafune, M. Fukugita and Y. Oyanagi: Phys. Rev. **D 1 6** (1977) 772.
24. The lower bound ~20 % is derived by making use of the experimental results, 2?r(0'—>x(3.45)?0i?r X(x(3.45)-+//^r)^0.5%[3] and £r(0'->z(3.45)r) <2.5%.
25. G. Feinberg and J. Sucher: Phys. Rev. Letters **35** (1975) 1740; J. S. Kang and J. Sucher: Paper No. 659 submitted to this Conference.
26. H. Lipkin: Fermilab Conf. 77/93 THY (1977).
27. R. Barbieri, R. Gatto and R. Kôgerler: Phys. Letters **6 0 B** (1976) 183.
28. At present the mass of the possible new resonance can be -3.17 GeV instead of -3.6 GeV.[3]
29. S. W. Herb, *et al:* Phys. Rev. Letters **39** (1977) 252.
30. W. R. Innés, *et al.:* Phys. Rev. Letters **39** (1977) 1240.
31. Ch. Berger, *et al.:* Phys. Letters **7 6 B** (1978) 243; C. W. Darden, *et al:* Phys. Letters **7 6 B** (1978) 246.
32. Y. Hara: Phys. Rev. **B 1 3 4 ,** (1964) 701; Z. Maki: Progr. theor. Phys. **31** (1964) 331.
33. S. L. Glashow, J. Iliopoulos and L. Maiani: Phys. Rev. **D2** (1970) 1285.
34. M. Kobayashi and K. Maskawa: Progr. theor. Phys. **49** (1973) 652.
35. See, also, H. Harari: Phys. Letters **5 7 B (1975)**

265; Ann. Phys. (N. Y.) **94** (1975) 391 ; L. Maiani: Phys. Letters **62B** (1976) 183; S. Pakvasa and H. Sugawara: Phys. Rev. **D14** (1976) 305; J. Ellis, M. K. Gaillard and D. V. Nanopoulos: Nucl. Phys. **B109** (1976) 213.

36. D. R. Yennie: Phys. Rev. Letters **34** (1975) 239; See. also, J. J. Sakurai: Paper No. Ill submitted to this Conference (to be published in Priysica A); K. Ishikawa and J.J. Sakurai: Paper No. 1110 submitted to this Conference.
37. J. L. Rosner, C. Quigg and H. B. Thacker: Paper No. 879 submitted to this Conference.
38. E. Eichten and K. Gottfried: Phys. Letters **66B** (1977) 286.
39. C. Quigg and J. L. Rosner: Phys. Letters **71B** (1977) 153; **72B** (1978) 462.
40. See, also, Y. Muraki: Progr. theor. Phys. **41,** (1969) 473; K. Mori, Y. Muraki and M. Nakagawa: Paper No. 471 submitted to this Conference.
41. D. Pignon and C. A. Piketty: Phys. Letters **74B** (1978) 108.
42. See, for example, O. Nachtmann : *Proc. Int. Symp. Photon and Lepton Physics, Hamburg, Aug. 1977* A. De Rûjula, H. Georgi and H. D, Politzer: Ann. Phys. (N. Y.) **103** (1977) 315; W. A. Bardeen, A.J. Buras, D. W. Duke and T. Muta: Fermi-Lab-Pub-78/42 THY.
43. R. G. Moorhouse, *et al. :* Nucl. Phys. **B124** (1977) 285.
44. W. Celemaster, H. Georgi and M. Machacek: Phys. Rev. **D17** (1978) 879; W. Celemaster and F. Henyey: UCSD-10P10-191 (1978).
45. R. Levine and Y. Tomozawa: UMHE 78-41 (1978). These authors derived a potential which interpolates the *r->0* limit (3.9) and r**->oo** limit *rjlna,* by solving a renormalization group equation in QCD.
46. H. Grosse and A. Martin: Réf. TH. 2513-CERN (1978).
47. H.J. Schnitzer: Paper No. 47 submitted to this Conference.
48. N. Isgur and G. Karl: Paper No. 13, 14 and 16 (Phys. Letters **72B** (1977) 109) submitted to this Conference.
49. There is also an interesting application of a rotating stringlike bag model, in which the quarks reside at the ends, to both *q*‰ and *q*q* baryons. See, P. J. G. Mulders, A. Th. M. Aerts and J. J. de Swart: Paper No. 386 submitted to this Conference.
50. R. Brandelik, *et al :* Phys. Letters **70B** (1977) 132.
51. G. Feldman: rapporteur talk at this Conference.
52. J. Ellis, M. K. Gaillard and D. V. Nanopoulos: Nucl. Phys. **B100** (1975) 313. See, also, G. Altarelli, N. Cabibbo and L. Maiani: Phys. Rev. Letters **35** (1975) 635, N. Cabibbo and L. Maiani: Phys. Letters **73B** (1978) 418.
53. M. Suzuki: LBL Report, LBL-7948 (1978).
54. M. Peshkin and J. L. Rosner: Nucl. Phys. **B122** (1977) 144, A. Pais and S. B. Treiman: Phys. Rev. **D15** (1977) 2529.
55. P. Rapidis, *et al.:* Phys. Rev. Letters **39** (1977) 526; D. L. Scharre, *et al:* Phys. Rev. Letters **40** (1978) 74.
56. M. Matsuda, N. Nakagawa, K. Odaka, S. Ogawa and M. Shin-Mura: Progr. theor. Phys. **59** (1978) 1396.
57. M. Matsuda, T. Matsushita, K. Odaka and S. Ogawa: Paper No. 351 submitted to this Conference.
58. S. P. Rosen: Paper No. 125 submitted to this Conference and Phys. Rev. Letters **41** (1978) 3.
59. See, also, Y. Hara: talk given at the Symposium on New Particles at Research Inst, for Fundamental Physics, Kyoto University, Feb. 1978.
60. Observed value of Michel parameter, />=0.83±0.12±0.15is incompatible with *V+A (p=-0.15),* but compatible with *V-A(p=0.53).* (See ref. 51.)
61. N. Kawamoto and A.I. Sanda: Phys. Letters **76B** (1978) 446; F. Gilman and D. Miller: Phys. Rev. **D17** (1978) 1846.
62. A. S. Carroll, *et al.:* Phys. Rev. Letters **32** (1974) 247; V. Chaloupka, *et al:* Phys. Letters **61B** (1976) 487; W. Bruckner, *et al:* Phys. Letters **67B** (1977) 222; S. Sakamoto, *et al:* Paper No. 1058 submitted to this Conference.
63. P. BenkheirL *et al :* Phys. Letters **78B** (1977) 483.
64. H. Braun, *et al:* Phys. Letters **60B** (1976) 481; C. Evangelista, *et al:* Phys. Letters **72B** (1977) 139; P. Pavlopoulos, *et al:* Phys. Letters **72B** (1978) 415; A. A. Carter, *et al:* Phys. Letters **67B** (1977) 117; S. Bartalucci, *et al:* DESY 77/59 (1977); G. Bemporad: Hamburg International Conference on Lepton and Photon Interactions, Aug. 1977; C. Cosme, *et al:* presented by F. Laplanche, Hamburg International Conference on Lepton and Photon Interactions, Aug. 1977; G. Cosme, *et al:* Phys. Letters **67B** (1977) 231; B. Esposito, *et al:* Phys. Letters **68B** (1977) 389; C. Bacci, *et al:* Phys. Letters **68B** (1977) 393; G. Barbiellini, *et al:* Phys. Letters **68B** (1977) 397.
65. G. F. Chew: *Proc. Third Europ. Symp. NN Interaction, Stockholm, 1976* (Pergamon Press) p. 515.
66. J. L. Rosner: Phys. Rev. Letters **21** (1968) 950, 1422 (E); J. L. Rosner: Phys. Reports **11C** (1976) 189.
67. See, also, Y. Hara, Progr. theor. Phys. **47** (1972) 1624.
68. P. G. O. Freund, R. Waltz and J. L. Rosner: Nucl. Phys. **B13** (1969) 237.
69. M. Imachi, S. Otsuki and F. Toyoda: Progr. theor. Phys. **55** (1976) 551; **57** (1977) 517.
70. X. Artru: Nucl. Phys. **B85** (1975) 442.
71. G. C. Rossi and G. Veneziano: Nucl. Phys. **B123** (1977) 507.
72. A. Chodos, R. L. JafFe, K. Johnson, C. B. Thorn and V. F. Weisskopf : Phys. Rev. **D9** (1974) 3471.
73. A. Chodos, R. L. Jaffe, K. Johnson and C. B. Thorn: Phys. Rev. **D10,** (1974) 2594.
74. T. A. DeGrand, R. L. Jaffe, K. Johnson and K. Kiskis: Phys. Rev. **D12** (1975) 2060.

75. Linear baryons have been proposed by T. Inami, K. Kawarabayashi and S. Kitakado in Paper No. 284 submitted to this Conference.

76. Baryons and exotic hadrons in the quark-string model have been studied in a semi-classical approach by looking for classical rigid rotator solutions by K. Kikkawa, T. Kotani, M. Sato and M. Kenmoku in Paper No. 356 submitted to this Conference.

77. M. Imachi and S. Otsuki: Progr. theor. Phys. **58** (1977) 1657, 1660; **59** (1978) 1290.

78. F. Toyoda and M. Uehara: Progr. theor. Phys. **58** (1977) 1456; T. Inami, K. Kawarabayashi and S. Kitakado: Phys. Letters **72B** (1977) 127.

79. M. Uehara: Progr. theor. Phys. **59** (1978). 587.

80. Y. Eylon and H. Harari: Nucl. Phys. **B80** (1974) 349.

81. Upper and lower bounds of $a_4^2(0)$, $a_2\backslash 0)$ and $a_0^2(0)$ have been derived by K. Igi and S. Yazaki in Paper No. 365 submitted to this Conference.

82. M. Imachi, S. Itoh and S. Otsuki: Paper No. 538 submitted to this Conference.

83. M. Uehara: SAGA 78/2 (1978).

84. See, also, A. W. Hendry and I. Hinchliffe: Paper No. 253 submitted to this Conference.

85. R. L. Jaffe and K. Johnson: Phys. Letters **60B** (1976) 201; R. L. Jaffe: Phys. Rev. **D15** (1977) 267, 281.

86. As to the present experimental status of the scalar nonet, see, Cashmore, rapporteur talk at this Conference.

87. These two types of states do not mix when the orbital angular momentum *L* (of the diquark about the antidiquark) is large because of the following reason. From one-gluon-exchange we obtain a spin-spin interaction between the two quarks of the following form,

$$a = l$$

where *C* is proportional to the quark-gluon coupling a_s and depends on the overlap of the quark spacial wave functions with the potential. Two quarks may couple to a 3* or 6 of color SU(3) and a spin singlet or triplet. The diquark system can thus be in the following representations with the eigenvalue *AE* of the spin-spin interaction

(color, spin)	Flavor	ΔE
(3*, 1)	3*	$-8C$
(6, 3)	3*	$-(4/3)C$
(3*, 3)	6	$(8/3)C$
(6, 1)	6	$4C$

Since the color magnetic forces between the quarks and the antiquarks are short-ranged, their effect should decrease rapidly with *L*. At high *L*, therefore, there are no interaction which mixes the color-triplet diquark and the colorsextet diquark. For detail see ref. 88.

88. Chan H. M. and H. Hogaasen: Phys. Letters **72B** (1977) 121; (1978) 400; Nucl. Phys. **B136** (1978) 401. See, also, R. L. Jaffe: Phys. Rev. **D17** (1978) 1444.

89. K. Johnson and C.B. Thorn: Phys. Rev. D13 (1977) 1934.

90. The M-baryonium may correspond to the M_4^4 meson in the junction model shown in Fig. 7.3 (f). The decays of M_4^4 into M_4^4+M, $B+B_h\backslash$ $B+B+$ $B+B$ etc. are allowed, but the decay of M_4^4 into $B+B$ is forbidden. There is also a possibility that there may be a new type of strings, at the ends of which diquarks and antidiquarks in color sextets are tied. The allowed decay of the new *qqqq* state tied with the new string M_4^4 is M_4^4-> M_4^4+M.

91. Quantitative calculation of qqqq states has been carried out in (3 + 1) dimentional lattice gauge theory by Sakai and Hikosaka, and they have obtained the result, *M* (qqqq)/M(N) =2.8; S. Sakai and K. Hikosaka: Paper No. 250 submitted to this Conference. In this model the results, M(ûO«M(/0)«O.82Af(N), have already been obtained by Banks, *et al.*; T. Banks, *et al.*: Phys. Rev. D15 (1977) 1111.

92. I. M. Barbour and D. K. Ponting: Paper No. 258 submitted to this Conference.

93. H. M. Chan: private communication.

94. See, however, B. Schrempp and F. Schrempp: Phys. Letters 55B (1975) 303.

95. LP. Auer, *et al.:* Phys. Letters 67B (1977) 113; 70B (1977) 475; Phys. Rev. Letters 41 (1978) 354; Paper No. 447 submitted to this Conference.

96. N. Hoshizaki: Progr. theor. Phys. 57 (1977) 1099; 58 (1977) 716; Paper No. 520 submitted to this Conference.

97. See, also, S. Furuichi, M. Matsuda and W. Watari: Nuovo Cimento 23A (1974) 375.

98. R. A. Arndt: Phys. Rev. 165 (1968) 1834; Los Alamos Nucleon-Nucleon Workshop (June, 1978), H. Suzuki: Progr. theor. Phys. 54 (1975) 143.

99. K. Hidaka, *et al.:* Phys. Letters 70B (1977) 497.

100. T. Kamae, *et al:* Phys. Rev. Letters 38 (1977) 468.

101. T. Kamae and T. Fujita: Phys. Rev. Letters 38 (1977) 471.

102. The symbol B^2 for dibaryon resonances has been invented by A. Yokosawa at this Conference.

103. However, a model where a deuteron is considered as the two nucléon bound state with a small mixture of the six-quark bound state has been proposed. It has been shown that this six-quark state determines the deuteron form factors when $\#^2>1(\mathrm{GeV}/c)^2$. See, A. P. Kobushkin: Paper No. 994 submitted to this Conference; Y. Kizukuri, M. Namiki and K. Okano: Waseda Univ. preprint (1978).

104. R. L. Jaffe: Phys. Rev. Letters 38 (1977) 195 and 617(E).

105. P. J. G. Mulders, A. Th. M. Aerts and J. J. de Swart: Paper No. 386 submitted to this Conference. See, also, P. J. G. Mulders, A. Th. M. Aerts and J. J. de Swart: Phys. Rev. Letters 40 (1978) 1543.

106. K. Fujii: Butsuri 28 (1973) 989.

P6: eN, ***fîN,*** rN Reactions

Chairman: W. PAUL

Speaker: E. GABATHULER

Scientific Secretaries: K. KONDO
T. SATO

(Tuesday, August 29, 1978; 14: 00-15: 00)