NUP-A-93-7
Fermilab Library
0 1160 0033092 2

NUP-A-93-7

Three "New" Points of View on Hadron Spectroscopy *

Shin Ishida
Atomic Energy Research Institute,
College of Science and Technology,
Nihon University, Tokyo 101

Abstract

I shall present the following three new (or more appropriately, not conventional) points of view, based upon the recent investigations by our group, on hadron spectroscopy:

I. Light-quark hybrid meson

There occurs doubling of 4 nonets with $J^{PC} = (0,1,2)^{++}$ and 1^{+-} between $(q\bar{q})_p$ states and $(q\bar{q}g)_s$ states.

II. Hybrid $c\bar{c}g$-meson

There exists one more set of χ-states, $\chi_{cg} = (c\bar{c}g)_s$'s, than the ordinary one $\chi_c = (c\bar{c})_p$.

III. Light- and heavy-quark meson mass spectra

Spectroscopy of confined hadron systems is described by a simple covariant harmonic Oscillator with a universal spring constant independently of quark flavors.

NAME | I D No. | M.S.
FERMILAB LIBRARY MAR 22 1994
RETURN TO FERMILAB LIBRARY

*Talk presented given at the Mini-Work Shop on Meson Spectroscopy, KEK, Tsukuba, Japan, November 6-7, 1992.

Part I **Light-quark Hydrid Meson**

In this part we shall summarize the essennce of our recent two published works[1,2] and of an unpublished work[3].

[Massive constituent gluon]

We assume that

"a constituent gluon inside of hadrons becomes massive" as

		const.(effective)mass	current mass
gluon		400 ~ 800 Mev	0
quark	u,d	~ 300 Mev	2 ~ 3 MeV
	s	~ 500 MeV	200 MeV

In this connection, remember that a quark has its constituent mass, inside of hadrons, different from the current mass.

(Background)

Theoretical backgrounds for non-zero effective gluon mass come from various sides, see for examples:

C.Bernard (1982): Lattice QCD calculation.[4]

J.E.Mandula and M.Ogilvie (1987): Phenomenological view point.[5]

J.M.Cornwall (1979): Dynamical mass generation in coninuum QCD.[6]

[Level structures of hybrid meson]

The essential structure is given by two harmonic oscillators concerning the relative coordinates ρ and λ (see, Fig.1). The total spin J of hybrid mesons is given as a sum of the two orbital angular momenta L_ρ and L_λ, the spin of the quark-antiquark subsystem S (= 0 or 1), and the spin of the gluon S_g (= 1). The parity is given by $P = (-1)^{L_\rho + L_\lambda}$, while the charge-conjugation parity of the neutral states is given by $C = (-1)^{L_\rho + S + 1}$. In Table I we have shown the level structure up to the first excited states. Here it is worthwhile to note that in the first excited level there exist ecotic J^{PC} states which never appear in the $q\bar{q}$ states.

TABLE I. Level structures of hybrid mesons. Exotic quantum number states are underlined. The mass range for respective levels is estimated in a way described in the text.

N^a	L_ρ	L_λ	S	Σ^b	J^{PC}			Mass (GeV)
			0	1		1^{+-}		
0	0	0		0		0^{++}		1.3–1.8
			1	1		1^{++}		
				2		2^{++}		
			0	1	0^{-+}	$\underline{1^{-+}}$	$\underline{2^{-+}}$	
	1	0		0		1^{--}		1.8–2.2
			1	1	$\underline{0^{--}}$	1^{--}	2^{--}	
				2	1^{--}	2^{--}	3^{--}	
1								
			0	1	$\underline{0^{--}}$	1^{--}	2^{--}	
	0	1		0		$\underline{1^{-+}}$		2.0–2.4
			1	1	0^{-+}	$\underline{1^{-+}}$	$\underline{2^{-+}}$	
				2	$\underline{1^{-+}}$	$\underline{2^{-+}}$	$\underline{3^{-+}}$	

[a] $N = N_\rho + N_\lambda$.
[b] $\Sigma = S + S_g$.

The mass of the ground states may be estimated simply as a sum of the masses of their constituents:

$$M_0(q\bar{q}g) = m_q + m_{\bar{q}} + m_g,$$

taking the values $m_n = 385$ MeV (half of the ρ-meson mass) for n quarks (n denoting u or d quark), $m_s = 510$ MeV (half of the ϕ-mesons) for s quarks, and $m_g = 500 \sim 800$ MeV for gluons.

The mass of the first excited states may be estimated, using the mass formula

$$M^2(q\bar{q}g) = M_0^2(q\bar{q}g) + N_\rho \Omega^{(\rho)}_{q\bar{q}g} + N_\lambda \Omega^{(\lambda)}_{q\bar{q}g},$$

with

$$\Omega^{(\rho)}_{q\bar{q}g} = \frac{\sqrt{7}}{8}\left[2 + \frac{m_g}{m}\right]\Omega_{q\bar{q}},$$

$$\Omega^{(\lambda)}_{q\bar{q}g} = \frac{3}{8}\left[2 + \frac{m_g}{m}\right]\left[\frac{2m + m_g}{m_g}\right]^{1/2}\Omega_{q\bar{q}},$$

where $N_\rho(N_\lambda)$ and $\Omega^{(\rho)}(\Omega^{(\lambda)})$ are, respectively, the number and the values of $\rho(\lambda)$ oscillator quantum and $\Omega_{q\bar{q}} = \sqrt{32mK}$. Here the values of $\Omega^{(\rho)}$ and $\Omega^{(\lambda)}$ are

$\Omega_{q\bar{q}} \approx 1.26\Omega_{n\bar{n}} \approx 1.45$ GeV^2 ,

$\Omega^{(\rho)}_{n\bar{n}g} \approx 2.07\Omega_{n\bar{n}} \approx 2.39$ GeV^2 for $n\bar{n}g$ systems;

$\Omega^{(\rho)}_{s\bar{s}g} \approx 1.12\Omega_{s\bar{s}} \approx 1.48$ GeV^2,

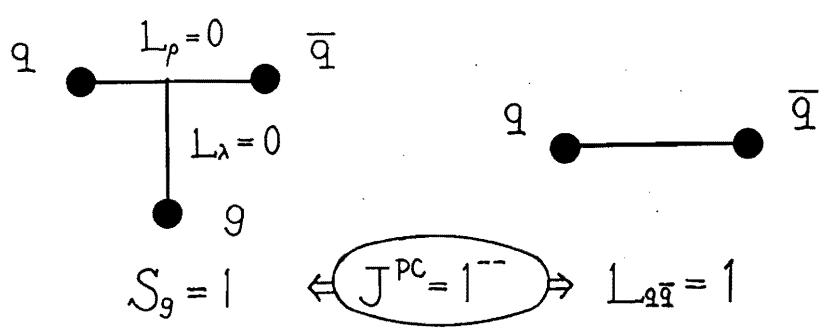
$\Omega^{(\lambda)}_{s\bar{s}g} \approx 1.98\Omega_{s\bar{s}} \approx 2.62$ GeV^2 for $s\bar{s}g$ systems,

which are obtained by using the value of $\Omega_{n\bar{n}} = 1.15$ GeV^2 determined from the ρ-meson trajectory and the tentatively fixed value of $m_g = 700$ MeV and by simply assuming the potential strength K to be flavor-independent. In Table I we have shown the mass range of respective levels estimated as above.

[Doubling of levels between ground $q\bar{q}g$- and P-wave $q\bar{q}$-states]

Our level structures of hybrid mesons have an interesting and important feature. The ground states of our hybrid mesons have completely the same quantum numbers as the P-wave $q\bar{q}$ mesons.

Fig.1 Doubling between $q\bar{q}g$-and $q\bar{q}$-states



$$J^{PC} = (0^{-+}, 1^{--}) \otimes 1^{--}$$
$$= 1^{+-} \oplus (0, 1, 2)^{++}$$

This is due to the fact that a massive S-wave gluon inside the hybrid mesons plays a similar role to a P-wave quantum in the $q\bar{q}$ mesons. Moreover, the mass of the ground-state hybrid mesons is expected to be in the range of $1.3 - 1.8$ GeV, which is just the mass range for the P-wave $q\bar{q}$ mesons. Thus, in such a mass region, there exists the doubling of four flavor nonets with quantum numbers $J^{PC} = (0, 1, 2)^{++}$

and 1^{+-} between the hybrid and the $q\bar{q}$ mesons with nearly equal masses with each other.

It is notable that in our model the lowest-lying states have positive partity. This is in strong contrast to the bag model, where the corresponding states have negative parity and are expected to lie in the mass range of $1-2$ GeV. In the case of the MIT bag model, there are two modes of gluon: namely, transverse electric (TE) mode and transverse magnetic (TM) one. TE and TM modes are due to the multipole expansion of the color-electromagnetic field inside the bag. The parity of the TE dipole mode, which is expected to be of the lowest energy, is given by $P_{TE} = (-1)^{J+1} = +$; accordingly, the ground-state hybrid mesons have negative parity.

["Variant Mass and Width" of a_1 meson]

In a recent experiment on the peripheral $\pi^- p$ charge-exchange reaction at KEK it has been observed that the a_1 meson has very different values of mass and width, compared to the ones thus far obtained with the diffractive process, as well as compared to the ones recently obtained with the central-collision process. We argue that this "variant mass and width" of the a_1 meson is due to interference between the two "doubling" partners with the same quantum number, an ordinary $q\bar{q}$ meson and a hybird $q\bar{q}g$ meson.

(a_1 problem) The experimental facts are in detail as follows:

In the recent experiment at KEK[7] on the peripheral charge-exchange reaction $\pi^- p \to M^0 n$ they have observed a peak in the $\rho\pi$ channel with the same quantum numbers $(I^G, J^{PC}) = (1^-, 1^{++})$ as the $a_1(1260)$. Its mass and width are 1122±17 MeV and 254±11 MeV, respectively, which are very different from $m = 1280\pm30$ MeV and $\Gamma = 300\pm50$ MeV thus far obtained with the diffractive process as well as from $m = 1208\pm15$ MeV and $\Gamma = 430\pm50$ MeV recently obtained from an analysis of the centrally produced $\pi^+\pi^-\pi^0$ system[8], while its mass value is close to the one simply obtained from the τ decay process[9] without any complex manipulations but its width is much narrower. There has been a big controversy concerning the mass and width of the a_1 meson for quite some time.

These experimental situations are summarized in Table II. From our viewpoint the above facts may be simply interpreted by supposing that in all cases the experiments are generally observing the superposition of two states with the same quantum numbers, the $q\bar{q}$ state with a somewhat lower mass and the $q\bar{q}g$ state with a higher mass. Since these two states have generally different production and/or decay properties, the observed properties of this "superposed particle" may change depending upon the status of the experiments as follows.

The "a_1 meson" obseved in the peripheral-collision process and in the τ decay process has a considerably lower mass compared to that obsevered in the diffractive process and in the central-collision process. Our interpretaion is that in the former "gluon-poor" processes we are observing the superposed particle mainly with the $q\bar{q}$ component (having a lower mass and a narrower width, that is a_1), while in the latter "gluon-rich" processes the superposed particle having nearly equally the $q\bar{q}(a_1)$ and $q\bar{q}g(a_{g1})$ components, where the latter component has a higher mass and a broader width compared to those of the former component.

(Theoretical decay spectra of "a_1" in comparison with experiments)

We give here the results of our simple analyses of the three recent experiments:

Used parameters We have taken the following values of parameters

r and θ (ratio and relative phase of the amplitude a_{g1} to that of a_1)

Gluon-poor process:

Peripheral (KEK)
τ decay (ARGUS) $\quad r = 0.25 \quad \theta = 0$

Gluon-rich process:

Central (WA76) $\quad r = 0.6 \quad \theta = 0$

mass and width (MeV)

	Mass	Γ	
a_1	1080	350	← fitting of lower mass region
a_{g1}	1300	600	← theory for decay property

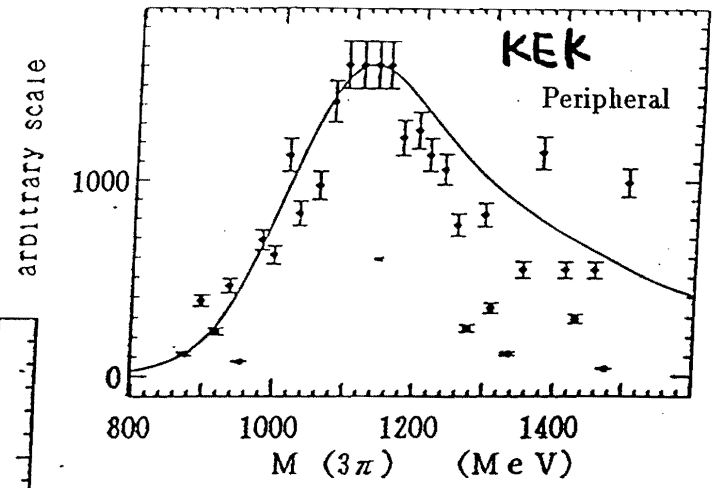
Decay spectra are given in Fig.2. Our theoretical curves reproduce well all three experimental data obtained, respectively, in the peripheral production process, in the τ-decay process and in the central production process. The respective values of r, 0.25, 0.25 and $r = 0.6$ seem to be reasonable from our physical consideration.

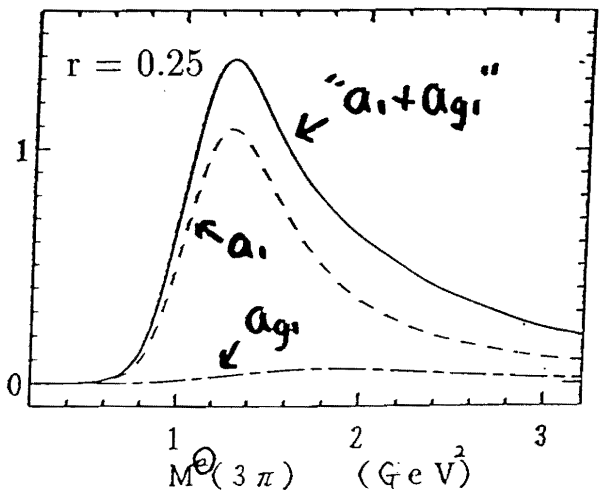
Table II Properties of a_1 meson obtained from various experiments

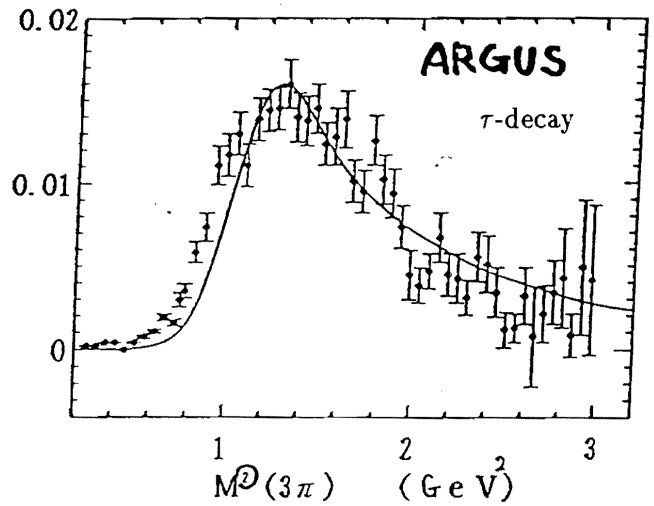
Meson	Production processes	Observed channels	Mass(MeV)	Width(MeV)
$a_1(1260)$	Diffractive process $\pi^- p \to \pi^+\pi^-\pi^- p$ at 63 and 94 GeV	$\rho\pi$	1280 ± 30	300 ± 50
	Peripheral process $\pi^- p \to \pi^+\pi^-\pi^0 n$ at 8.06 GeV	$\rho\pi$	1122 ± 17	254 ± 11
	Central process $pp \to p_f\pi^+\pi^-\pi^0 p_s$ at 300 GeV	$\rho\pi$	1208 ± 15	430 ± 50
	τ decay (DELCO)	$\rho\pi$	$1056 \pm 20 \pm 15$	$476 \,^{+132}_{-120} \pm 54$
	(Mark II)	$\rho\pi$	$1194 \pm 14 \pm 10$	$462 \pm 56 \pm 30$
	(ARGUS)	$\rho\pi$	1046 ± 11	521 ± 27
	(MAC)	$\rho\pi$	$1166 \pm 18 \pm 11$	$405 \pm 75 \pm 25$

Fig.2

Decay Spectra
of "a_1" meson in
three experiments



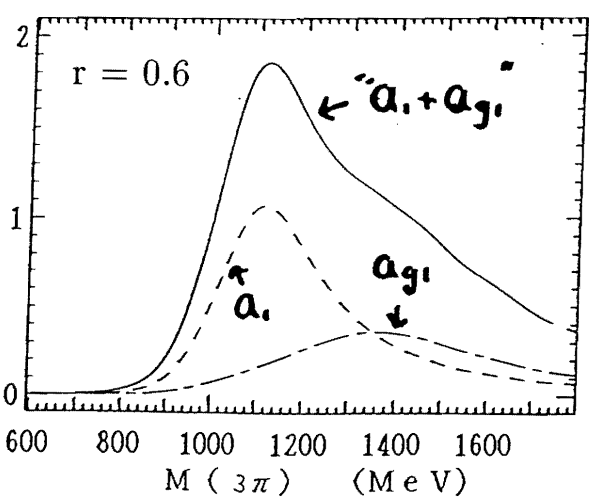


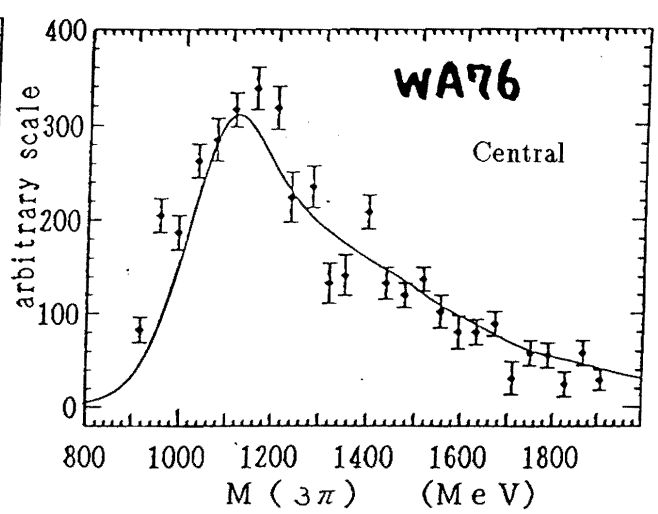


$$\text{“}a_1\text{”} = a_1 + r \cdot a_{g1}\ ;$$

$$a_1 \quad \left\{ \begin{array}{lcl} m & \sim & 1080 \quad \text{(MeV)} \\ \Gamma & \sim & 350 \end{array} \right.$$

$$a_{g1} \quad \left\{ \begin{array}{lcl} m & \sim & 1300 \\ \Gamma & \sim & 600 \end{array} \right.$$

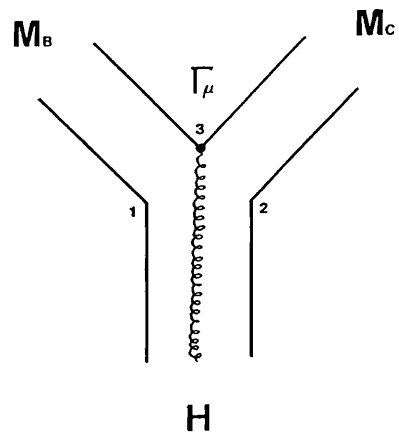




[Decay properties of the ground-state hybrid mesons]

We have investigated decay properties of the ground-state hybrid messons, assuming the decay mechanism shown in Fig.3, in the frame work of the covariant oscillator quark model (COQM)[12].

Fig.3
Decay mechanism of hybrid mesons into two ordinary mesons



(Deay mechanism)

The covariant effective Hamiltonians for respective decay processes are unifiedly given by the overlapping among the multi-local initial hybrid meson field H and the two final $q\bar{q}$ meson fields, $\bar{M}_B$ and $\bar{M}_C$.

$$I_{int} = g\int d^4x_1 d^4x_2 d^4x_3 [\bar{M}_{c\beta}^{\ \delta}(x_3, x_2)\Gamma_{3\nu}{}_{\delta}^{\gamma}\bar{M}_{B\gamma}^{\alpha}(x_1, x_3)H_{\alpha\nu}^{\beta}(x_1, x_2, x_3) + H.C.].$$

Here $\Gamma_{3\nu}$ represents the quark-gluon vertex operator. The only one parameter, coupling constant g, is determined by the decay width of $f_1(1420)$, a plausible candidate of the hybrid mesons according to our previous work[10].

Coupling constant $g \Leftarrow \Gamma(f_1(1420) \rightarrow K^*K) \approx 55$MeV.

(Characteristic features of decay properties)

From our analysis we see that our theoretical decay widths for the respective hybrid-meson nonets with J^{PC} have the following characteristic features.

1^{+-} *nonet.* All members have a narrow width of less than about 100 MeV, except for h_{g1} with $\Gamma \approx 150 - 220$ MeV.

0^{++} *nonet.* All members have a narrow width of less than 100 MeV, except for f_{g0} with $\Gamma \approx 130 - 150$ MeV, in contrast with the corresponding $q\bar{q}$ states, which are expected generally to have a very broad width of several hundred MeV.

1^{++} *nonet.* All members have a very broad width of more than about $400 - 500$ MeV, except for the $f_{g1}(1420)$, which is our "input" hybrid meson. This is due to the fact that generally this nonet couples strongly with the PV channel [$P(V)$ stands for pseudoscalar (vector) mesons], while the $f_{g1}(1420)$ has a very small threshold energy for its dominant decay channel $K^*\bar{K}$.

2^{++} *nonet.* Each member of this nonet has a width of about $100 - 300$ MeV,

depending upon its mass, which is moderate for observation, and they couple strongly with the VV and/or PV channels, while very weakly with the PP channel.

Thus we can understand why only the $f_{g1}(1420)$ has been observed out of the members of the 1^{++} nonet, and we see that there is a good chance for observing the members of the 1^{+-} , 0^{++}, and 2^{++} nonets, which generally have a moderate width for their obsevation. Here it may be worthwhile to note that the above features are related to the "rest rule" concerning the overlapping of our relativistic spin wave function at zero threshold energy.

[Experimental candidates for ground-state hybrid mesons]

By making use of our predicated decay properties of the ground-state hybird mesons we have tried to select several possible candidates for the respective members of their four nonets out of still-unclassified observed mesons. Here we show only the present status of our assignments for them in Table III.

Table III

Present status of our assignments for the ground-state hybrid-meson nonets.

		$I=1$	$I=\frac{1}{2}$	$I=0$	
$^{2S+1,2\Sigma+1}L_J$	J^{PC}	$n\bar{n}g$	$n\bar{s}g, s\bar{n}g$	$n\bar{n}g$	$s\bar{s}g$
$^{13}S_1$	1^{+-}	$b_{g1}(1300)$	$K_{g1}(1650)$		
$^{31}S_0$	0^{++}	$a_{g0}(1320)$		$f'_{g0}(1240)$	$f'_{g0}(1525)$
$^{33}S_1$	1^{++}	$a_{g1}(1400)$	$(*)^a$	$f_{g1}(1420)$	$(**)^b$
$^{35}S_2$	2^{++}			$f_{g2}(1640)$	

[a]This state is expected to be seen only as a background effect because of its very broad width.

[b]This state may be observed only through interference effects between doubling partners because of its broad width. See the text.

[Excited states of hybrid mesons]
Recently possible existence of several "new" mesons, which show some extra-ordinary behaviors in production process, has been reported experimentally.

(Possible candidates)

① $\pi^- p$-charge exchange process (D. Alde et al. 1989)

$$\pi^- p \rightarrow \eta + X^0(1920) \quad J^{PC} = 1^{-+} \ ?$$
$$\hookrightarrow \eta\eta'$$

S.S.Gershtein, A.K.Likhoded (IHEP)'s paper reports:

② $\pi^- p$-diffraction process (S.Bitvukov etal. 1991)

VES(IHEP)

$$\pi^- A \rightarrow A + X(1814)$$
$$\hookrightarrow \pi^-\eta\eta \quad J^{PC} = 2^{-+} \ ?$$
$$\hookrightarrow \pi^-\eta\eta'$$

③ Same IHEP VES set up (G.V.Borisov et al.)

$$X(1620) \quad J^{PC} = 1^{-+} \ ?$$
$$\hookrightarrow \pi\rho,\ \pi f_1,\ \pi\eta,\ \pi\eta'$$

Here we only point it out that "These may be candidates for the 1st excited hybrid mesons" predicted in our scheme (the levels with a bold line listed in Table I).

Part II **Hybrid $c\bar{c}g$-Meson**

In this part we shall report on a preliminary result of consideration on the properties of hybrid charmonium states, $c\bar{c}g$-meson.

If the light-quark hybrid mesons discussed in the previous section are proved truely to exist, we may expect theoretically equally the existence of various hybrid states.

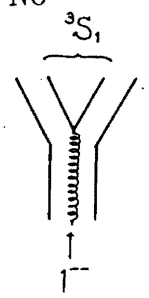
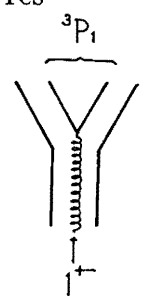
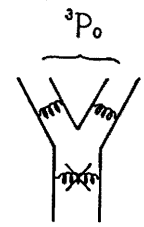
One of the most interesting ones may be hybrid mesons with heavy quarks, where we can expect equally the doubling of states. In the case of the ground-state hybrid $c\bar{c}g$ mesons, their mass is expected to be around $m_{J/\psi} + m_g \approx 3.8$ GeV (or a little lower, considering an effect of running gluon mass), while their doubling partners χ_c and h_c mesons (which are P-wave $c\bar{c}$ states) have a mass of $3.4 - 3.5$ GeV. Thus, in this case, since the mass values of doubling states are largely separated from each other compared to their characteristic decay width of about 10 MeV or less, there may be no chance of interference between the doubling states. These gluonic charmonium states are also very interesting experimentally, and have been discussed[11)] especially in connection to the Super LEAR project. However, the properties of our $c\bar{c}g$-mesons with a massive constituent gluon are very much different from those of conventional ones similary as in the case of light quark hybrid mesons.

[H$(c\bar{c}g)_G$ in three typical models]

First we compare the properties of ground-state hybrid mesons H$(c\bar{c}g)_G$ in the three typical theoretical models, the COQM[12], the Bag Model[11] and the Flux-tube Model[13], considering their decays into the OZI-allowed open-charm channel. The qualitaive features of respective models are collected and compared each others in Table IV.

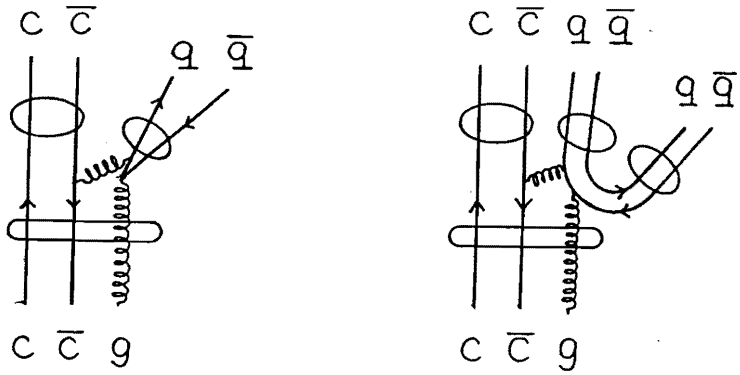
The quantum numbers of the lowest mass states are very much different between the COQM and the others. Accordingly the selection rules in the decays of H_G into the two $q\bar{q}$-mesons, which are valid strictly in the static limit, are drastically different with each others. The considerations in the static limit may be effective int the two cases of COQM and the Bag Model, where the mass of H_G may be in the close region to the corresponding threshold of the OZI-allowed open-charm two meson channels. The case of Flux-tube Model may be irrelevant since of the expected masses of H_G being much higher. Both in the former two cases of COQM and Bag Model the situations, whether the OZI-allowed channels may be closed or not, are quite critical. It is required more detailed quantitative investigations to predict anything definite concerning these processes.

Table IV Comparison of OZI-allowed decays of H_G into two mesons in the three typical models

	COQM	Bag M	Flux-tube M
J^{PC}	$0^{++}, 1^{++}, 2^{++}; 1^{+-}$.	$0^{-+}, 1^{-+}, 2^{-+}; 1^{--}$.	$0^{\mp\pm}, 1^{\mp\pm}, 2^{\mp\pm}; 1^{\mp\mp}$
$H \to (M\ M)_s$ decay in static limit			
$\to M_s \quad M_s$	Yes	No	No
$\to M_s \quad M_p$	No	Yes	Yes
			
open-charm channel	$D\bar{D}$	$D\bar{D}^{**}$	$D\bar{D}^{**}$
m_{thr}	3.7Gev	4.3Gev	4.3Gev
m_{H_G}	$m_J + m_g$	$m_J + (\frac{1}{2}m_{gg} \sim m_{gg})$	
	$3.1 + (0.4 \sim 0.8)$	$3.1 + (0.8 \sim 1.5)$	
	$3.5 \sim 3.9$ Gev	$3.7 \sim 4.5$ Gev	<u>much higer</u>
OZI-rule allowed channel	may or may not be closed	may or may not	not

[H_G-strong decay into OZI-forbidden and $c\bar{c}$-triggered channels]
Second we consider the strong decays of H_G into the $c\bar{c}$-meson triggered OZI-forbidden two- or three-meson channels shown in Fig.4.

Fig.4 Strong decays of H_G into OZI-forbidden and $c\bar{c}$-triggered channels



As is seen from Fig.4, the partial width Γ for these processes contains a factor of α_s^3. Now we show the main relevant decay channels of the respective H_G particles, which are allowed in the static limit, in both the cases of above two models.
(Main decay channels)

	Bag M (Close) TE mode			COQM(ours)	
		$m_{th.}$(GeV)			$m_{th.}$(GeV)
0^{-+}	$(\chi_0\ \eta)_s$	4.0	0^{++}	$(\eta_c\ \eta)_s$	3.5
1^{-+}	$(\chi_1\ \eta)_s$	4.1	1^{++}	no	
1^{--}	$(\psi\ (\pi\pi)_s)_s$	3.4	1^{+-}	$(\psi\ \eta)_s$	3.6
2^{-+}	$(\chi_2\ \eta)_s$	4.2	2^{++}	no	

Comparing the threshold energies, given above, of respective channels with the expected masses of H_G's (Table IV), we see that the relevant channels generally might be closed or have a very small phase volume even if opend. This situation is the same in both the models, although the relevant respective channels are very much different in them.

Thus we may conclude that there is a large possibility of all relevant channels being closed or of very small partial width. Then radiative decays of H_G's become relatively much inportant in search of them.

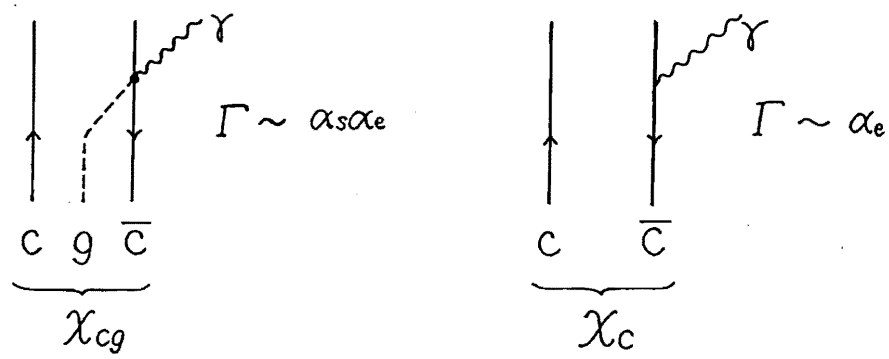
[$H_G(c\bar{c}g) \to M(c\bar{c}) + \gamma$]

As was mentioned, our H_G's have same quantum numbers as the respective $\chi(c\bar{c})$ states and have the similar (a little higher) masses. Thus we can estimate the radiative decay widths of χ_c's simply (see Fig.5) as

$$\Gamma(\chi_{cg} \to \psi + \gamma) = \underbrace{\alpha_s}_{1/100\sim1/10} \underbrace{\Gamma(\chi_c \to \psi + \gamma)}_{(0.1\sim0.5)MeV} = (1 \sim 50)keV$$

Here it may be notable that in our scheme there is a possibility of the physical χ's to be mixed states of $\chi_c(c\bar{c})$ and $\chi_{cg}(c\bar{c}g)$. In this connection it is interesting that the experimental decay widths for both $\psi'(2s) \to \chi_c + \gamma$ and $\chi_c \to \psi + \gamma$ seem to be generally smaller (by a fair amount) than the most of theoretical estimates: Obviously the mixing, with the above estimate, will reduce the theoretical values for both the decay widths.

Fig.5 Radiative decays of χ_{cg} and χ_c



Part III Light-and/or Heavy-Quark Meson Mass Spectra

In this part we shall report on the essential results of our unified investigation[15,16] of the meson mass spectra in the framework of COQM*). For these two decades since our first work[14] we have applied it to various problems with successful results. However, our applications have been, until recently, limited mainly within the light-quark hadron systems, where the oscillator wave funcitons proved to be describing well the confined states (unperturbed by QCD). We have recently found an interesting possibility that the mass spectroscopy of confined meson systems is unifiedly described by a simple covariant harmonic oscillator with a universal spring constant, independently of quark flavors.

General Framework of COQM

The general framework of NRQM may be called the LS-coupling scheme, where L(S) denotes the NR quark orbital (spin) angular momentum. Historically NRQM was proposed with the three light-quarks known at that time, and their general framework was called the $SU(6)_{FS}\otimes 0(3)_L$ scheme, where $SU(6)_{FS}$ represents the symmetry for an amalgamated three light-flavor and Pauli-spin space. Presently also with heavy quarks it has the symmetry scheme of $F\otimes 0(3)_L\otimes SU(2)_S$, F denoting the corresponding flavor symmetry. The general framework of COQM may be called the boosted LS-coupling scheme, where the quark orbital angular momentum and the quark spin are boosted separately, and has the symmetry of $F\otimes$(Boosted-$0(3)_L)\otimes$(Boosted-$SU(2)_S$). Here the 3-dimensional oscillators on the quark space-coordinates are extended to the 4-dimensional ones on the space-time coordinates and the NR Pauli spinors are extended to some covariant spinors.

*) The COQM has a long history of development since the bilocal theory by Yukawa 1950 and has been developed by many authoers (mostly in Japan). As for its review and the references, see an article[12] given recently by us.

Mass Operators and Space-Time Wave Equations

The bilocal field, representing unifiedly a system of $q\bar{q}-$mesons, is supposed, concerning its space-time part, to satisfy the equation

$$[\sum_{i=1}^{2} \frac{1}{2m_i} \frac{\partial^2}{\partial x_{i\mu}^2} - U(x_1, x_2)]\Phi(x_1, x_2) = 0, \tag{3.1}$$

where $m_1(m_2)$ is the parameter corresponding to quark (antiquark) mass, and the confinement potential U is taken to be of the four-dimensional Hooke-type

$$U(x_1, x_2) = \frac{1}{2}K(x_1 - x_2)_\mu^2.$$

Equation (3.1) is rewritten, in terms of the center-of-mass coordinates and the relative coordinates defined by

$$X_\mu \equiv \frac{1}{m_1 + m_2}(m_1 x_{1\mu} + m_2 x_{2\mu}), \qquad x_\mu \equiv x_{1\mu} - x_{2\mu},$$

as

$$[\frac{\partial^2}{\partial X_\mu^2} - \mathcal{M}^2(x)]\Phi(X, x) = 0 \tag{3.2}$$

with the squared-mass operator of the form

$$\mathcal{M}^2 = dH = d[-\frac{1}{2\mu}\frac{\partial^2}{\partial x_\mu^2} + U(x)], \tag{3.3}$$

$$d = 2(m_1 + m_2), \qquad \mu = \frac{m_1 m_2}{m_1 + m_2}.$$

Here it is to be noted that H has a similar form to the energy of relative motion in the NR potential model except for it now being represented by Lorentz four-vectors $x_{i\mu}$'s instead of three-vectors $\boldsymbol{x}_i$'s.

As is wellknown, the "redundant" relative-time freedom causes to make a serious difficulty, namely, the existence of space-like solutions with $(\text{mass})^2 < 0$. This difficulty may be resolved by making the relative time freedom "frozen" by supposing

$$< p_\mu x_\mu >=< p_\mu q_\mu >= 0, \tag{3.4}$$

where <A> means to take "expecation values" of A concerning internal space-time wave functions, $p_\mu(q_\mu)$ being a conjugate momentum to $X_\mu(x_\mu)$. The subsidiary condition (3.4) may be satisfied generally in the two typical ways with the indefinite-metric or with the definite-metric. (We choose the latter way). Then Eq.(3.4) is replaced by

$$p_\mu a_\mu^\dagger |phys. >= 0, \tag{3.5}$$

(a_μ and a_μ^+ being the oscillator variables) and in the rest system with $\boldsymbol{p}= 0$, the mass operator takes the three-dimensional form,

$$\mathcal{M}^2 = \Omega(a_i^\dagger a_i) + M_0^2. \tag{3.6}$$

, where we have introduced phenomenological paramenters M_0's, representing the masses of ground states with respective flavor combinations.

It is remarkable that our definite metric wave function has a desirable asymptotic behavior on the relative time , and leads to phenomenologically desirable meson and baryon form factors.

A Universality of Spring Constant and Flavor-dependence of Oscillator Quantum

In COQM the $q\bar{q}$-meson mass-squared spectra is described effectively by the three-dimensional harmonic oscillator Eq.(3.6).

Accordingly their leading orbital Regge trajectories are described by straight lines with a slope Ω^{-1} for squared masses. This has been a well confirmed phenomenological fact for light quark systems.

Now in our scheme the oscillator quantum Ω for respective $q\bar{q}$-meson systems are given as

$$\Omega = 2(m_q + m_{\bar{q}})^{3/2}(m_q m_{\bar{q}})^{-1/2}K^{1/2} \tag{3.7}$$

in terms of relevant quark masses and spring constants K's which may, in principle, have some flavor dependence. Here we introduce a new physical assumption:

(P). "The spring constant K of Hooke-type potential is a universal constant independent of quark flavors".

About two decades ago, when only three light flavors had been known, one of the present authors proposed[12)] a universality of oscillator quanta for all hadron systems. Now our new postulate(P) predicts that respective oscillator quanta in the different flavor-configuration systems are generally different and mutually related, through Eq.(3.7), in terms of (constituent) quark masses and a universal spring constant.

Here it may be worthwhile to note that the predictions of the two (new and old) universalities are roughly similar for light-quark systems, while they differ, as will be shown shortly, very much for the systems with heavy quarks.

Phenomenological analysis of the Universality

The mass spectra of confined quark-anti-quark meson systems are described by the three-dimensional harmonic oscillator (3.6) in our scheme. The respective oscillator quanta Ω's are determined by Eq.(3.7). In fixing the (constituent) quark mass values

we simply assume, following the ordinary procedure, that they are given*) by the half of corresponding vector-quarkonium masses as (in GeV)

$$m_n \equiv m_u = m_d = \frac{1}{2}M_\rho = 0.384, \qquad m_s = \frac{1}{2}M_\phi = 0.510,$$
$$m_c = \frac{1}{2}M_{J/\psi} = 1.55, \qquad m_b = \frac{1}{2}M_\Upsilon = 4.73, \tag{3.8}$$

The value of K is determined from the Regge slope of ρ meson trajectory through Eq.(3.7) as

$$K = 0.107(GeV)^3 \qquad from \qquad \Omega_\rho(n\bar{n}) = 1.15(GeV)^2. \tag{3.9}$$

Then we can predict all the Ω values in any quark-flavor systems, which are collected in Table V.

Table V. Values of oscillator quanta Ω in $(\mathrm{GeV})^2$.
$\Omega = 2(m_q + m_{\bar{q}})^{3/2}(m_q m_{\bar{q}})^{-1/2}K^{1/2}$. m_q is fixed by identifying it as a half of the mass of corresponding vector meson quarkonium. $\Omega(n\bar{n}) \equiv 1.15$ is an input.

$g\bar{g}$	$n\bar{n}$	$n\bar{s}$	$s\bar{s}$	$n\bar{c}$	$s\bar{c}$	$c\bar{c}$	$n\bar{b}$	$s\bar{b}$	$c\bar{b}$	$b\bar{b}$
Ω	1.15	1.25	1.32	2.28	2.17	2.30	5.62	5.05	3.80	4.03

As a matter of fact, our mass operator Eq.(3.6) describes the mass spectra of unperturbed confined meson systems. As is wellknown, actual mass spectra of hadrons are affected not a little by the one-gluon-exchange (OGE) effects. In our previous work[17] we have investigated extensively the mass spectra of the light-quark system, considering the OGE-effects in COQM. One of the main results was that the spin-independent Coulomb-type and orbit-orbit-like parts induce the mass-reduction of a fair amount for the radially excited S-wave states, [illegible] little the orbitally excited states.

Remembering the above fact, in this work we have compared our predicted Ω values with the experiments, by simply plotting the observed mass-squared values of mesons versus numbers of oscillator quanta N in the cautiously classified various cases, where our theory predicts the linear trajectories with respective slopes Ω. Here we show only the results on the leading orbital Regge trajectories:

In Fig.6 the present situations of the orbital excitation (in this case N =L ; L being the orbital angular momentum) for the light-quark systems are given, respectively; in (a) $\rho-$ and $\pi-$, (b) $\omega-$, (c) K^*- and $K-$, and (d) $\phi-$trajectories.

*) We may also fix m_q in another way as, for example, $m_n = (1/2)\sqrt{(m_\pi^2 + 3m_\rho^2)/4} = 0.335$, which induces little change in the features of our results.

In Fig.7 the present situations of the orbital exctitation ($N = L$) for the light- and/or heavy-quark systems are given, respectively, in (a) $c\bar{c}-$, (b) $c\bar{n}-$, (c) $c\bar{s}-$, and (d) $b\bar{b}-$ trajectories.

In these figures all the data points are extracted from the Meson Summary Table in the reference[18], unless being specially referred.

Fig.6 Leading orbital-Regge-trajectories for light-quark mesons

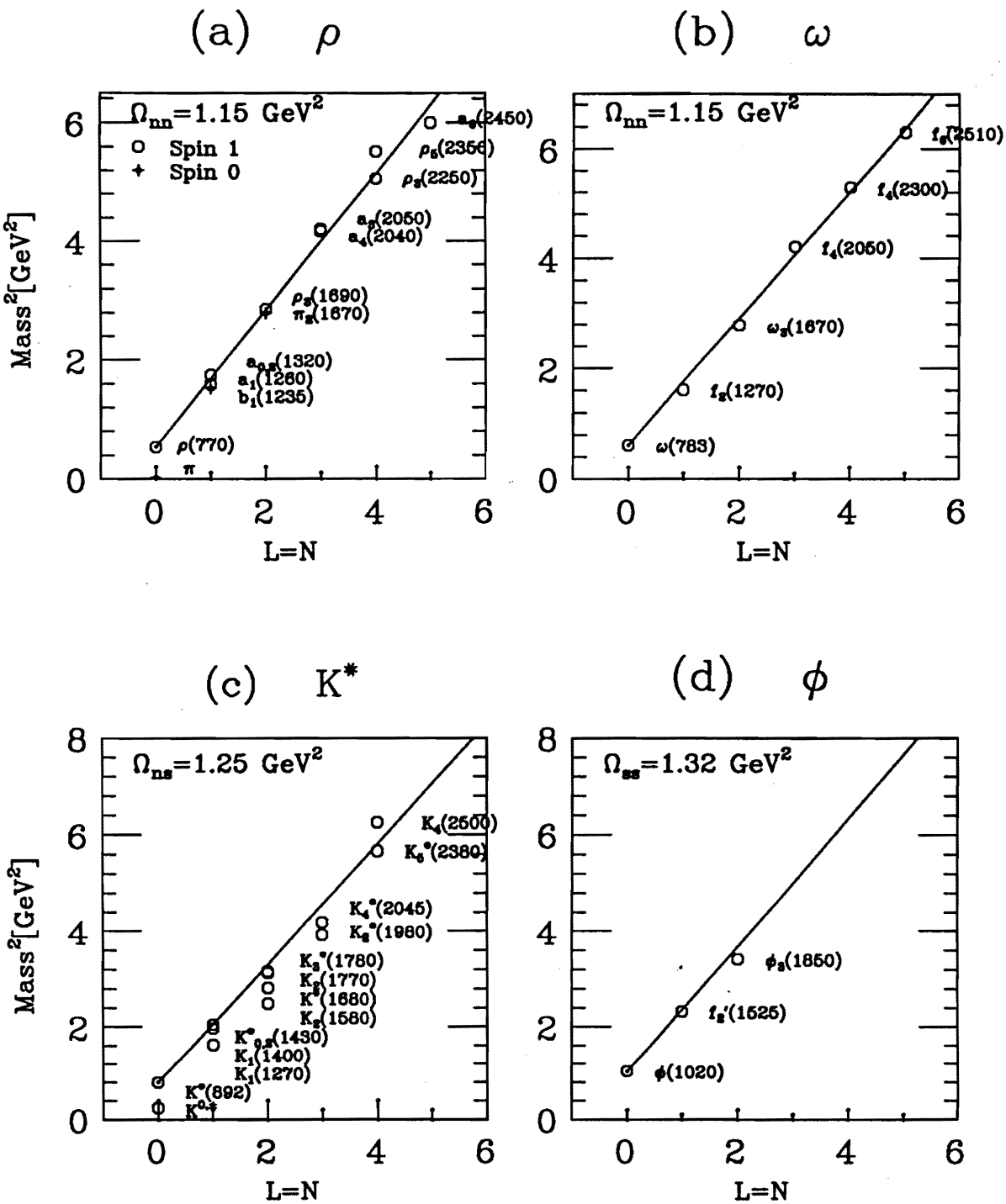
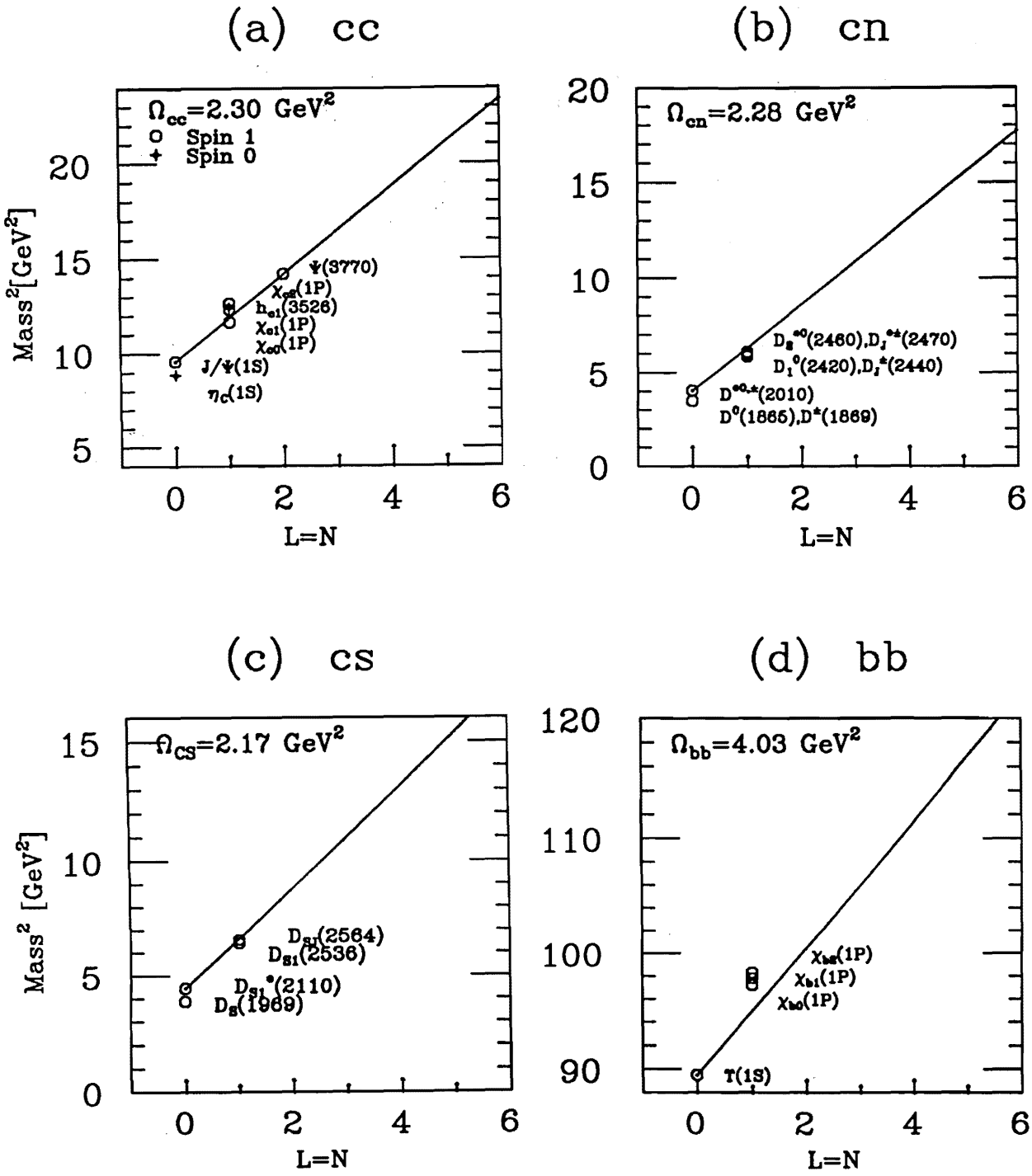


Fig.7 Leading orbital-Regge-trajectories for light-and/or heavy-quark mesons



Concluding Remarks

These figures seem to show that our universality is valid experimentally. Thus we may conclude that Yukawa's expectation given long ago in his bilocal theory, which is one of the important bases of COQM, is now actually realized in the hadron world.

The experimental meson mass spectra generally deviate from the predicitions of simple harmonic oscillator. We have found that this deviation has a similar characteristic behavior to that expected from the OGE-effects. The extensive quantitative analysis from this line, of the meson mass spectra with all possible flavor combinations, is now under progress[16)], and will be published separately.

Acknowledgements

The contents of this talk are based upon the investigations done in collaboration with the members of our research group. The author should like to express his deep gratitude to Dr. M. Oda, Dr. K. Yamada, Dr. H. Sawazaki and T. Tanimoto.

References

1) S. Ishida, M. Oda, H. Sawazaki and K. Yamada, Prog. Theor. Phys. 88 (1992) 89.

2) S. Ishida, H. Sawazaki, M. Oda and K. Yamada, Phys. Rev. D47 (1993) 179.

3) S. Ishida, M. Oda, H. Sawazaki and K. Yamada, in preparation.

4) C. Bernard, Phys. Lett. 108B (1982) 431: Nucl. Phys. B219 (1983)341.

5) J. E. Mandula and M. Ogilvie, Phys. Lett. B185 (1987) 127.

6) J. M. Cornwall, Nucl. Phys. B157 (1979) 392.

7) A. Ando et al., KEK Preprint 90-65 (1990).

8) T. A. Armstrong et at., Z. Phys. C48 (1990) 213.

9) H. Albrecht et al., Z. Phys. C33 (1986) 7.

10) S. Ishida, M. Oda, H. Sawazaki and K. Yamada, Prog. Theor. Phys. 82 (1989) 119.

11) See, for examples, F. E. Close, paper presented at Workshop on Physics at Super LEAR, Zürich, October 1991.

12) S. Ishida and M. Oda, in the Proceedings of "Extended Objects and Bound Systems" ed. by O. Hara, S. Ishida and S. Naka (World Scientific, Singapore. 1992).

13) N. Isgur, R. Kokoski, and J. Paton, Phys. Rev. Lett. 54 (1985) 869.

14) S. Ishida, Prog. Theor. Phys. 46 (1971) 1570 and 1905. See also, R. P. Feynman, M. Kislinger, and F. Ravndal, Phys. Rev. D3 (1971) 2706.

15) S. Ishida and M. Oda, NUP-A-93-3; Nihon Univ. Preprint (1993).

16) T. Tanimoto, Master Thesis; Nihon University (1993).

17) S. Ishida and K. Yamada, Phys. Rev. D35 (1987) 265.

18) Particle Data Group, Phys. Rev. D45 (1992).