New Particles

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I. Introduction

Almost every child asks his parents as to where he/she has come from? In his/her own way the child is worrying about the origin of life. After some more years he starts enquiries about the mysteries of the universe and when he has somewhat matured he bothers about the constituents of matter. These three are probably the most fundamental problems which have been worrying human beings for centuries. In this talk however my aim is modest, I will only concentrate on the progress that we have made in the last two years in understanding the third question.

Since last few years it is widely believed that quarks and leptons are the constituents of nature and that their number is equal and atleast four. Whenever I think about the status of quarks I am reminded of the following quotation of T.H. Huxley 'It is the customary fate of new truth to begin as heresy and end as superstition'. Undoubtedly, quark is no more heresy though probably not superstition as yet:

In the quark model the mesons are made of $q\bar{q}$ while the baryons are made out of qqq. All the hadronic systems can be divided into following 3 categories:

1. $Q_1\bar{Q}_2$ Q_1 being charm or heavy quark
2. $Q_1\bar{q}_2$ q = u, d, s quark
3. All other combinations.

System (1) i.e. $b\bar{b}$, $c\bar{c}$ etc. to atleast zeroth approximation can be described by two-body Schrödinger eq. so that one can extract a lot of information regarding quark-antiquark potential from a study of such bound systems.

System (2) i.e. D ($c\bar{u}$), F($c\bar{s}$) etc. are not so interesting as $m_{Q\bar{q}} \gtrsim m_q$ so that to zeroth approximation it is equivalent to one-body problem that is almost independent of m_Q. Thus such systems are always relativistic.

System (3) includes all Baryons, Baryoniums, old mesons etc. This whole category is terribly complex and probably will not shed much light about strong interaction between quarks. Hence I will not talk about these objects any more, but will mostly concentrate on mesons belonging to category (1).

Throughout my talk I will assume that the quark dynamics is described by QCD, a non-Abelian gauge theory of strong interactions in which colored quarks interact via exchange of an octet of colored, massless, gluons. In particular I will make use of the following ingredients of QCD (which are no doubt valid at the hand-waving level but a rigorous proof is lacking): (1) QCD is asymptotically free (2) quarks are in 3 colors and are confined (3) all flavor dependence stems from quark mass effects (4) the interaction between stationary quarks is given by local, spin and flavor independent potential (5) OZI rule.

I will follow the following plan: In Sec.II, I will review the present status of the charmonium model. In Sec. III, I will have a quick look at the " open charm " as revealed by D and F mesons. In Sec.IV, I will talk about the startling discovery of heavy lepton τ and ν_τ. Now that one has six leptons it is natural to expect that there must be six quark flavors too. Lo and behold ! fifth quark b(beauty) has already been found. Fermilab and DESY both have seen $b\bar{b}$ bound states Υ, Υ' and I will devote quite a bit of time in discussing hidden beauty (sec.V). With so much support for quark-lepton symmetry one is almost sure that the sixth quark t (taste) must be there. The properties of the $t\bar{t}$ bound system are speculated in Sec.VI. In last section I summarize our present understanding about the constituents of matter.

II. Charmonium

Just within four years, the J/ψ-spectroscopy has become one of the richest in hadron physics[1]. Fig.(1) shows the known charmonium levels upto 3.8 GeV. Qualitatively this spectrum had been predicted just after J/ψ and ψ' were discovered (but much before other levels were found) on the basis of a simple minded charmonium model. According to this model J/ψ, ψ', ... are the bound states of charm quark-antiquark ($c\bar{c}$) system which to atleast zeroth approximation can be described by nonrelativistic dynamics. The

$c\bar{c}$ potential is assumed to be

$$V(r) = -\frac{4K}{3r} + V_c(r) \qquad (2.1)$$

where the first term is the one-gluon exchange potential which is expected to dominate at short distance while the second term is the quark confining potential which dominates at long distance. Taking lattice gauge theory as a guide it is usually assumed that $V_c(r)=ar$ with "a" being flavor independent*. This model gives good qualitative fit to the data not only for $a \simeq 0.2$ GeV^2, $K(m_\psi^2) \simeq 0.2$, $m_c = 1.6$ GeV but also when $K(m_\psi^2) = 0.4 \sim 0.5$. A la QED it is clear that the potential $-\frac{4K}{3r}$ must generate spin forces by vector exchange. However nothing is known about the way spin forces are generated by $V_c(r)$ which can be considered to arise from multiple gluon exchanges.

Using ^3P_J data one can only shown that[4] $V_c(r)$ cannot be spin-independent. Further, if $V_c(r) = ar$ it cannot generate spin forces by vector exchange alone**. Infact $V_c(r) = ar$ can simulteneously explain $J/\psi - \eta_c$, $\psi' - \eta_c'$ and ^3P_J

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* It must be admitted that this choice of $V_c(r)$ is not on the same firm footing as the one-gluon exchange potential. Even $V_c(r) = ar^\eta$ $0 \lesssim \eta \lesssim 2$ is consistent[2] with the experimentally observed ordering $E(1S) < E(1P) < E(2S) < E(1D)$).

** Whether $V_c(r)$ generates spin forces by vector exchange or not can be decided by accurate determination of 1^1P_1 mass as in the case of vector exchange $M(^1P_1)$ has been shown[5] to be $\frac{1}{9}(21M(1^3P_1)-5M(1^3P_2)-7M(1^3P_0)) = 3562 \pm 10$ MeV.

splittings only and only if a fraction f (~ 0.1) of ar generates spin forces by vector plus color moment exchange and (1-f) by scalar exchange[6] (for color moment $\lambda = 4 \sim 5$ $K(m_{\psi}^2) = .4 \sim .5$ and a and m_c as before).

There is a serious problem for this model if one identifies x(2.83) and x(3.45) with η_c and η_c' respectively. One finds that there is serious disagreement between theory and experiment[7] (Table 1).

Table 1 : M1 transition rates for charmonium

Process	Theory	Experiment
$B(J/\psi \to \chi(2.83) + \gamma)$	40 %	1.7 %
$B(\psi' \to \chi(3.45) + \gamma)$	9 %	2.5 %
$B(\psi' \to \chi(2.83) + \gamma)$	4 %	1 %
$B(\psi' \to \chi(3.45) + \gamma) \times B(\chi(3.45) \to \psi + \gamma)$	8×10^{-6}	$(6 \pm 4) \times 10^{-3}$

This is really a serious problem because even for light mesons where nonrelativistic quark model is not expected to give good results, theory and experiment agree within factor of 2 to 3.

Two solutions have been proposed to the M1 trouble : (1) x (2.83) and x(3.45) are not η_c and η_c' and that the actual η_c and η_c' are there within 100 and 50 MeV of J/ψ and ψ' respectively. In this case detection of η_c and η_c' is going to be quite difficult. But then what are

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and $x(3.45)$ has been suggested[8] that these Baryonium states i.e. $x(2.83)$ is a $c\bar{c}q\bar{q}$ ($q \equiv u,d$) and $x(3.45)$ is a $c\bar{c}s\bar{s}$ state. In the former case we expect two 0^+ mesons one with $I = 0$ and other with $I=1$. Bag model calculations indicate[9] that while $x(3.45)$ may indeed be a baryonium state, $x(2.8)$ is too low to be a candidate for it. (2) The newly discovered level $x(3.6)$* is η_c' [10]. This level has been detected in $\psi' \to J/\psi + \gamma$ decay and one has experimentally

$$B(\psi' \to \chi(3.6)+\gamma)\, B(\chi(3.6) \to J/\psi+\gamma) = (2.8 \pm 1.2)\times 10^{-3} \qquad (2.2)$$

On the other hand theoretically we expect that

$$B(\psi' \to \chi(3.6)+\gamma) \simeq 0.5\,\%$$
$$\Gamma(\chi(3.6) \to J/\psi+\gamma) = 10 \text{ keV} \qquad (2.3)$$

Combining (2.2) and (2.3) we predict that

$$B(\chi(3.6) \to J/\psi + \gamma) \approx 60\,\% \qquad (2.4)$$

which is too large to be acceptable. In fact experimental result (2.2) indicates that $x(3.6)$ is a 0^+, 1^+ or 2^+ state so that both radiative transitions are E1 transitions.

Before finishing this discussion of hidden charm let me mention the discovery of $\psi''(3.77)$. Naively one would have thought that ψ' and ψ''. (Both being $J^{PC} = 1^{--}$ and

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* Note that the data is also consistent with a low mass state at 3.18 GeV.

differing in mass just by 80 MeV) should have similar decay rates, but experimentally ψ' is narrow while ψ'' is broad ($\Gamma_t(\psi'') \approx$ 28 MeV) and decays almost 100% to $D^0\bar{D}^0$ and D^+D^- even though it is only 30-40 MeV above the threshold for these decays. This is a dramatic confirmation of the OZI rule (See Fig. 2). Thus even though we have no rigorous understanding of OZI rule there is no doubt that it is a reality.

III. Charmed Mesons

3.1. Properties of D and D* :- If charm quark is present then in addition to J/ψ, ψ', ... one should also have charmed mesons $c\bar{q}$ (q u,d,s) possessing nonzero charm. By now pseudoscalar mesons D^+ ($c\bar{d}$), D^0(cu), F^+($c\bar{s}$) and vector mesons D^{*+}, D^{*0} and F^{*+} have been detected.

The masses of D^+ and D^0 are known very accurately[11] in $\psi''(3.77)$

$$M_{D^+} = 1868.3 \pm 0.9 \; , \; M_{D^0} = 1863.3 \pm 0.9 \text{ MeV}$$

$$\delta \equiv M_{D^+} - M_{D^0} = 5.0 \pm 0.8 \text{ MeV} \qquad (3.1)$$

Theoretically, using N.R. quark model one finds[12] $\delta = 6.5$ MeV.

In the standard WS-GIM model, the charged weak current is given by

$$j^+ = \cos\theta_c(\bar{u}d + \bar{c}s) + \sin\theta_c(\bar{u}s - \bar{c}d) \qquad (3.2)$$

θ_c being the Cabibbo angle. This leads to selection rules

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(2) $m_{\nu_\tau} < 0.25$ GeV, all data is consistent with $m_{\nu_\tau} = 0$.
(3) $\tau(\tau) < 3.5 \times 10^{-12}$ Sec. which is consistent with the theoretical prediction of 2.8×10^{-13} sec.

(4) Michel parameter $\rho = 0.66 \pm 0.13$ which strongly favours $\tau - \nu_\tau$ coupling to be V-A.
(5) $B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \simeq B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = 18\%$ rules out that τ is a paralepton. Most likely τ is a sequential lepton with its own lepton number and hence own nuetrino ν_τ.
(6) Various semilptonic decay rates are in good agreement with the theoretical calculations[19] as can be seen from Table 2.

Table 2: Semileptonic Branching Ratios of τ

Process (Branching ratio)	Exptl. (%)	Theory (%)
$\tau \to \pi \nu_\tau$	7.7 ± 1.3	10
$\tau \to K \nu_\tau$	< 1.6	0.5
$\tau \to \rho \nu_\tau$	24 ± 9	22
$\tau \to A_1 \nu_\tau$	10 ± 3	10

Now that one has six leptons, the quark-lepton symmetry demands that there must be two more quark flavors. Remarkably enough, in last one year we have firm evidence for fifth quark and we discuss it in the next section.

V. Beauty

5.1. Experimental situation:- Last year at Fermilab, Lederman group[20] found strong enhancement at 9.5 GeV in the mass spectrum of dimuons produced in the 400 GeV proton-nucleus collisions:

$$p + (Cu, Pt) \longrightarrow \mu^+ \mu^- + X \tag{5.1}$$

Their analysis shows that there are either two or three narrow peaks in this region which they named as Υ, Υ' (Υ'').

Recently both Υ and Υ' have been seen at DESY in e^+e^- collisions[21]. According to them

$$M_{\Upsilon} = 9.46 \pm .01 \, , \; M_{\Upsilon'} = 10.016 \pm .02 \quad GeV \tag{5.2}$$

$$M_{\Upsilon'} - M_{\Upsilon} = 558 \pm 10 < M_{\psi'} - M_{J/\psi} = 588.6 \quad MeV \tag{5.3}$$

$$\Gamma_{ee}(\Upsilon) = 1.2 \pm .2 \, , \; \Gamma_{ee}(\Upsilon') = 0.33 \pm .10 \; keV \tag{5.4}$$

$$B_{\mu\mu}(\Upsilon) = (2.6 \pm 1.4)\% \, , \; \Gamma_t(\Upsilon) > 25 \; keV \, (95\% \; C.L.)$$

$$\Gamma_t(\Upsilon)_{\text{Most Probable}} = 50 \; keV \, , \; \Gamma_{ee}(\Upsilon)/\Gamma_{ee}(\Upsilon') = 3.6 \pm .8$$

A reanalysis of the FNAL data with the above $M_{\Upsilon'} - M_{\Upsilon}$ value clearly shows Υ'' as a 13σ effect with $M_{\Upsilon''}$ predicted to be 10.38 GeV[22].

5.2. Analysis of the Data:-

(1) The most popular interpretation of these new mesons Υ, Υ' and Υ'' is that they are the ground and first two excited $^3S_1$ bound states ($J^{PC} = 1^{--}$) of fifth quark-anti-

quark($b\bar{b}$) system. It is a measure of the fantastic success of the $c\bar{c}$ interpretation of the ψ-family that there is almost no dissenting note about this interpretation.

(2) Since $\Upsilon, \Upsilon', \Upsilon''$ are narrow enough to have appreciable $\mu^+\mu^-$ branching ratio, they must all lie below the threshold for decay into a pair of mesons $Q\bar{q} + q\bar{Q}$. Thus whereas $s\bar{s}$ just fails to have a narrow $^3S_1$ state (ϕ-meson is just above $K\bar{K}$), $c\bar{c}$ has two and $b\bar{b}$ has 3 such narrow $^3S_1$ states i.e. as m_Q rises the number of narrow $^3S_1$ levels below Zweig threshold seem to increase.

(3) The story is similar to Nov.74 discovery of $J/\psi, \psi'$ except that unlike Υ', ψ' has never been clearly seen in pp interactions. The reason for this is that whereas the $\Upsilon, \Upsilon', \Upsilon''$ production rates are

$$B \left.\frac{d\sigma}{dy}\right|_0^{\Upsilon : \Upsilon' : \Upsilon''} = 1 : 0.3 : 0.15 \qquad (5.5)$$

(which are in excellent agreement with the theoretical prediction[23]) the corresponding ψ'/ψ production rate is only 2½ to 5%. This strongly suggests that

$$B(\Upsilon' \to \mu^+\mu^-) >> B(\psi' \to \mu^+\mu^-) \qquad (5.6a)$$

so that

$$\Gamma(\Upsilon' \to \Upsilon + \text{had}) << \Gamma(\psi' \to J/\psi + \text{had}) \approx 130 \text{ keV} \qquad (5.6b)$$

(4) Since $\Upsilon, \Upsilon', \Upsilon''$ are very narrow $m_b \approx 5$ GeV.

(5) The charge e_b of the beauty quark can be determined from $\Gamma_{ee}(\Upsilon,\Upsilon')$ which in the nonrelativistic approximation is given by

$$\Gamma(V \to e^+ e^-) = \frac{16\pi\alpha^2 e_Q^2 |\psi_Q(0)|^2}{M_V^2} \qquad (5.7)$$

$|\psi_Q(0)|$ being the appropriate bound state wave function at the origin. Now from the leptonic decay widths of ρ, ω, ϕ J/ψ Jackson has derived an empirical formula[24)]

$$|\psi_Q(0)|^2 \propto M_V^{1.89 \pm .15} \qquad (5.8)$$

so that $\Gamma_{ee}(V)/e_Q^2$ should be nearly independent of M_V. The plot of $\Gamma_{ee}(V)/e_Q^2$ vs M_V (Fig.3) shows that the data clearly favours $e_b^2 = \frac{1}{9}$ and not 4/9.

(6) The hadronic widths of Υ and Υ' can be calculated from QCD a la $J/\psi, \psi'$ cases. According to QCD[25)]

$$\Gamma_h(\Upsilon) = \Gamma(\Upsilon \to ggg) = \frac{1.6(\pi^2-9)\alpha_s^3(M_\Upsilon^2)|\psi_{1S}^b(0)|^2}{81\pi M_\Upsilon^2} \qquad (5.9)$$

where $\alpha_s(M_\Upsilon^2) \simeq 0.15$ is the quark-gluon coupling constant which is obtained from QCD by using the formula

$$\alpha_s(M_\Upsilon^2) = \frac{\alpha_s(M_\psi^2)}{1 + \frac{23}{12\pi}\alpha_s(M_\psi^2)\ln(M_\Upsilon^2/M_\psi^2)} \qquad (5.10)$$

with $\alpha_s(M_\psi^2) = 0.19$. Using the expression (5.7) for $\Gamma_{ee}(\Upsilon)$ in (5.9) we find that

$$\Gamma_h(\Upsilon) = 19.5\,\Gamma_{ee}(\Upsilon) \simeq 23.40 \pm 3.9 \text{ keV} \qquad (5.11)$$

which is somewhat smaller than the experimental value.

5.3. Potential Models:- Since according to QCD, the quarkonium potential is flavor independent hence the popular charmonium potential if correct should also explain the $b\bar{b}$ spectrum. About 2 years ago the m_Q dependence of the $Q\bar{Q}$ spectrum was studied[26] by using the potential (2.1)*. The predictions were (1) for $m_Q \gtrsim 3.5$ (6,10,14) GeV there will be 3 (4,5,6) narrow $^3S_1$ bound states below the Zweig threshold $(Q\bar{q}+\bar{Q}q)$*. Thus for $m_b = 5$ GeV, theory <u>predicts</u> 3 narrow $^3S_1$ states which seem to be confirmed by the experiments. (2) for $e_b = \frac{1}{3}$, it predicts that $\Gamma(\Upsilon,\Upsilon' \longrightarrow e^+e^-) = (0.7, 0.45)$ KeV which are crudely in agreement with the experiment numbers. (3) for $m_Q = 5$ GeV, this model predicts that $m_{\Upsilon'} - m_{\Upsilon} = 420$ MeV which is badly in disagreement with the experimental mass difference of 558 ± 10 MeV. Thus it is clear that the conventional charmonium model is not correct.

Two alternatives have been suggested in the literature (i) it has been shown[28] that if $K(m_\psi^2)$ is chosen to be $0.4 \sim 0.5$ instead of 0.2 then $m_{\Upsilon'} - m_{\Upsilon}$ is of the

* This prediction is not a special virtue of the potential (2.1) because for a wide class of potentials it has been shown[27] that $n \simeq 2\sqrt{\frac{m_Q}{m_c}}$ where n is the number of narrow $^3S_1$ bound states below Zweig threshold. For $m_c = 1.6$ GeV we then get the desired result.

right order of magnitude. Notice that for this value of K one has also been able to explain ^3P_J, $J/\psi - \eta_c$ and $\psi' - \eta'_c$ splittings. It should be noted that whereas $K(q^2)$ is the quark-gluon coupling constant at space-like q^2, $\alpha_s(q^2)$ is the corresponding one at time-like q^2 and at finite q^2 the two would in principle be different. Using data on $\Gamma_h(\Upsilon)$ and $\Gamma_{ee}(\Upsilon)$ it turns out that $\alpha_s(M_\psi^2) \simeq 0.20$ but data on scaling violations in deep-inelastic scattering indicates that[29] $K(m_\psi^2)$ could be as large as $0.4 \sim 0.5$. However, $\Gamma_{ee}(J/\psi, \psi')$ are now too large unless $m_c \simeq 1.2$ which gives rise to states which are much more relativistic. Similarly, for $m_b \simeq 5$ GeV, $\Gamma_{ee}(\Upsilon, \Upsilon')$ also come out to be too large.
(ii) Motivated by the apparent equality $M_{\psi'} - M_\psi = M_{\Upsilon'} - M_\Upsilon$, it has been suggested that $Q\bar{Q}$ potential is[30]

$$V(r) = c \ln\left(\frac{r}{r_0}\right) \qquad (5.12)$$

for which the level spacings can be rigorously shown to be independent of m_Q. For c=0.75 the charmonium spectra and $\Gamma_{ee}(\psi, \psi', \Upsilon, \Upsilon')$ can be fitted approximately. However for 1S, $\langle v^2/c^2 \rangle_{c\bar{c}}$ is again too large so that the use of N.R. approximation for charmonium is highly questionable. Besides, this model is bit crude and has no theoretical basis in the context of QCD. In conclusion, there is no quarkonium potential which can explain $b\bar{b}$ and $c\bar{c}$ spectra simulteneously. My feeling is that we are missing some vital point (may be N.R. appx. is bad for $c\bar{c}$) and that is why no model satisfactorily explains both $c\bar{c}$ and $b\bar{b}$ spectra.

5.4. Model Independent Results:- The other approach which has atracted some attention in the literature is to derive results which would be valid for a class of potentials. Some of these results are

(i) Relative Magnitude of 1s and 2s wave functions at the origin: For $c\bar{c}$ as well as $b\bar{b}$ systems we find from the data on the leptonic widths that $|\psi_{1s}(0)| > |\psi_{2s}(0)|$. Martin[31] has shown that the sufficient condition for

$$|\psi_{1s}(0)| \gtrless |\psi_{2s}(0)| \qquad (5.13)$$

is

$$-\frac{d^2V}{dr^2} \lessgtr 0 \quad \text{for all} \quad r. \qquad (5.14)$$

Notice that the quarkonium potential (2.1) satisfy $\frac{d^2V}{dr^2}<0$ for not only $V_c(r)=ar$ but even when $V_c(r)=ar^{\eta}$ with $0\leqslant\eta\leqslant 1$. Needless to say that the logarithmic potential also satisfies this condition. From Martin's sufficient condition it is clear that the $Q\bar{Q}$ potential cannot be convex. However nothing can be said about mixed potentials of the type $V(r) = -\frac{4k}{3r} + ar^{\eta}$ $(0<\eta\leqslant 2)$ which are consistent with the observed ordering of levels[2].

One open problem is to derive sufficient conditions for $|\psi_{2s}(0)|>|\psi_{3s}(0)|$ which is relevant in the context of a $^3S_1$ narrow bound state Υ''. My hunch is that (5.14) should suffice even for this case. This is because even for large n Gupta and Rajaraman have shown that[32)]

$$|\psi_{n,s}(0)| \gtrless |\psi_{n+1,s}(0)| \qquad (5.15)$$

provided $V(0)$ is finite and (5.14) is satisfied.

What are sufficient conditions for $|R'_{1p}(0)| \gtrless |R'_{2p}(0)|$? This is relevant question for $b\bar{b}$ system as 1p and 2p levels of it are expected to be below Zweig threshold and the decay rate for p-levels is proportional to $|R'_p(0)|^2$, R'_p being the derivative of the radial part of the $\ell=1$ wave function. Unfortunately it turns out[33)] that sufficient conditions can only be derived* for $|R'_{1p}(0)| < |R'_{2p}(0)|$ which is probably not relevant for the $b\bar{b}$ system.

(ii) Bounds on Decay Rates: Recently Rosner et al.[34)] have derived the lower bound $\Gamma_{ee}(\Upsilon,\Upsilon') \geq (2.6, 1.4)e_Q^2$ keV by making use of the inequality**

$$\frac{\partial}{\partial m_Q}\left(\frac{1}{m_Q}|\psi_{1s}(0)|^2\right) \geq 0 \qquad (5.16)$$

which is true for concave potentials ($d^2V/dr^2 < 0$ for all r).

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* Sufficient conditions have also been derived[33)] for $|d^\ell R_{1,\ell}(0)/dr^\ell| < |d^\ell R_{2,\ell}(0)/dr^\ell|$

** Sufficient conditions have also been derived[33)] recently for $\frac{\partial}{\partial m_Q}\left(\frac{1}{m_Q^{\ell+1}}\left|\frac{d^\ell R_{1,\ell}(0)}{dr^\ell}\right|^2\right) < 0$.

Strictly speaking, their derivation is not valid for Υ'. Besides, it is not clear if the quarkonium potential is really concave or not. Infact even the class of potentials

$$V(r) = -\frac{4k}{3r} + ar^{\eta} \qquad 0 < \eta \leq 2 \tag{5.17}$$

are consistent with the ordering of levels. Using the fact that for $V(r) = ar^{\epsilon}$ the m_Q dependence of $|\psi(0)|^2$ is given by

$$|\psi(0)|^2 \sim (m_Q)^{\frac{3}{2+\epsilon}} \tag{5.18}$$

and assuming that the m_Q -variation of $|\psi(0)|^2$ is smooth for the above potential, it has been shown that[35)]

$$\Gamma_{ee}(\Upsilon, \Upsilon') \geq (2.07, 1.12)\, e_Q^2 \quad keV \tag{5.19}$$

This again rules out $e_b^2 = \frac{4}{9}$. Using similar technique it has also been shown that[36)]

$$\Gamma(^3P_0^{b\bar{b}}, {}^3P_2^{b\bar{b}} \to had) \geq (68, 49) \ keV \tag{5.20}$$

5.5 Beautiful Mesons:- Undoubtedly the best way to detect beauty quark is to look for " beautiful 0^- mesons " $B^0(b\bar{d})$, $B^-(b\bar{u})$, $G^0(b\bar{s})$, $P(b\bar{c})$ and their vector counterparts. Since we have seen in Sec.III that as m_Q rises

$$M_{1^-}(Q\bar{q}) - M_{0^-}(Q\bar{q}) < m_{\pi}$$

hence we expect that B^*, G^*, P^* will decay dominantly by e.m. interaction i.e. $B^*(G^*, P^*) \longrightarrow B(G, P) + \gamma$.

Infact it has been shown that the hyperfine splittings for all of them are nearly equal[38)]

$$m_{B^*} - m_B \simeq m_{q^*} - m_q \simeq m_{p^*} - m_p \approx 30\ \text{MeV}$$

The lightest mesons B^0, B^- are expected around 5.3 GeV and we expect to see them soon in PETRA. The dominant decay modes of $B^{0,-}$ involve charmed mesons. The QCD calculations indicate[38)] that the nonleptonic decays of $B^{0,-}$ are not substantially enhanced in comparison to the semileptonic decays which are expected to be about 20%

The $B^0 - \bar{B}^0$ and $q^0 - \bar{q}^0$ mixing problems have been analysed and it has been claimed that if $m_t > 8$ GeV (m_t being the 6'the quark mass) then this mixing is much larger than $D^0 - \bar{D}^0$ and the CP-violating effects in $B^0 - \bar{B}^0$ may be even comparable to those in K^0-decays ![39)]

6. Taste

The situation as for today (Dec. 6, 78) is that there are 6 leptons and 5 quarks. What next ? I am very confident that there must exist 6'th quark "taste" (after charm and beauty what else !) as (i) Quark-lepton symmetry which has guided us so successfully demands it. (ii) If we want to build $SU(2)_L \otimes U(1)$ type of gauge theory then the cancellation of triangle anamalies require that no. of leptons be equal to quark flavors. (iii) Natural suppression of $\Delta S=1$ and $\Delta C=1$ effects to $O(G_F^2)$ can only be retained in that case. (iv) CP-violation can be naturally incorporated in $SU(2)_L \otimes U(1)$ gauge theory only if there are six quarks.

These arguments are so powerful that I am ready to bet for its existence*. Its expected charge is 2/3.

Remembering that $m_\phi = 1$ GeV, $m_{J/\psi} \simeq 3$ GeV, $m_\Upsilon = 9.5$GeV I conjucture that the lowest $^3S_1$ state of the $t\bar{t}$ system will be around 28-30 GeV so that**

$$m_t = \frac{m_\zeta \equiv (t\bar{t})_{3S_1}}{2} \simeq 15 \text{ GeV} \tag{6.3}$$

Using the analysis of the last section it is then clear that 6 narrow $^3S_1$ levels are expected in $t\bar{t}$ spectrum below the Zweig threshold $t\bar{q} + \bar{t}q$ (q=u, d).

Using Jackson's phenomenological formula $|\psi(0)|^2 \propto M_V^{1.89\pm.15}$ and $\Gamma_{ee}(\psi,\psi')$ the leptonic and hadronic widths of ζ and ζ' can be estimated. I find that[40)]

$$\Gamma_{ee}(\zeta,\zeta') \approx (3.6, 1.2) \text{ keV}; \quad \Gamma(\zeta,\zeta' \to \text{had}) \approx (11, 4.3) \text{ keV} \tag{6.4}$$

where $\alpha_s(M_\zeta^2) \simeq 0.13$ has been used. From here it turns out that

$$A_{t\bar{t}} \equiv \frac{|\psi_{1S}(0)|^2}{|\psi_{2S}(0)|^2} \simeq 6 \tag{6.5}$$

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* Let us hope that "taste" will be discovered by the time we again meet two years from now. I hope that the organizers will reveal the same taste as they have shown in selecting this pink city to celebrate beauty.

**In this context it is encouraging to note that dimuon data at Fermilab in pp collisions does not find any peak upto 18 GeV.

(note that $A_{b\bar{b}} \simeq 3.2 \pm .7$ and $A_{c\bar{c}} \simeq 1.6 \pm .6$) to be compared with the values 8 and 1 for Coulomb and linear potentials respectively. Thus the spectra of $t\bar{t}$ will be quite similar to the positronium spectra. It is really remarkable that the bound states of the lowest (massive) and heaviest constituents of nature i.e. e^+e^- and $t\bar{t}$ have similar spectra. This means that as m_Q rises strong interaction between quarks tend to become weak. The calculation of mass splittings, decay rate etc. for $t\bar{t}$ system is therefore quite straight-forward. In particular a la positronium one would expect that $\frac{m_{\Upsilon''} - m_{\Upsilon}}{m_{\Upsilon'} - m_{\Upsilon}} = \frac{32}{27}$.

7. Conclusions

There is no doubt that qualitatively the nonrelativistic quarkonium models explain the $c\bar{c}$ and $b\bar{b}$ spectra very well. However, at a quantitative level the situation is not so good and infact there is no model which satisfactorily explains both $c\bar{c}$ and $b\bar{b}$ families. With lot of data expected in coming two years from PETRA and PEP let us hope that the theory will be in a better shape by the time we meet next time. Anyway there is no doubt that by any standard, the success of the quarkonium model is phenomenal. Infact our understanding of $c\bar{c}$ and $b\bar{b}$ families is much better than that of lighter mesons.

The picture that emerges regarding constituents of nature is: we have 6 leptons and 5 quarks and it is almost certain that a sixth quark will be found soon. Is that the final number or the number of quarks and leptons will go on increasing ? Asymptotic freedom tells us that there cannot be more than 16 quarks[41]. A better bound is obtained from astrophysics[42] which indicates that number of leptons cannot be greater than fourteen. The point is that any new neutrino (with $m_\nu < 10$ KeV, $\tau(\nu)$ few sec) would have increased the energy density during the early stages of the expansion of the universe. As a result the rate of expansion is speeded up which affects the He^4 abundance in the universe. The observed upper bound of 29% on the cosmic helium abundance implies that number of neutrino types is $\leqslant 7$.

At a deeper level I wonder if quarks are indeed smallest constitutent of hadrons or not. It is quite possible that quark will turn out to be "just yet another sari of Draupadi"*.

Acknowledgements

It is a pleasure to thank Virendra Gupta, and S.P.Misra for constructive suggestions.

* In the classic Indian mythological epic " Mahabharatha" the story goes that once Dusyasan tried to take off the sari of Draupadi in front of everyone present in the court of his elder brother. She prayed Lord Krishna and the unbelievable happened ! As Dusyasan took of one sari, he found her covered with another sari and it went on and on. Finally he gave up .... ! !

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Figure Caption

Fig. 1. Charmonium spectrum

Branching ratios of Υ-decays; a = 7 ± 2% , b= 7 ± 2%, c = 7 ± 2%, d = 16 ± 3%, e = 23.4 ± 0.8%, f = 3.3 ± 1.0%, g < 2.5%, h < 1.0%, ig ≈ 0.5%, j < 1.7%, kl= 0.28 ± 0.12%. Data are taken from ref. (7), Feldman et al. ref. (1) and Phys. Lett. 75B, 1 (1978).

Fig. 2. Feynman diagram

(a) for OZI - allowed decay $\psi''(3.77) \longrightarrow D\bar{D}$

(b) for OZI - violating decay $\psi' \rightarrow J/\psi + 2\pi$

Fig. 3. $\Gamma(V \longrightarrow e^+e^-)/e_q^2$ versus M_V.

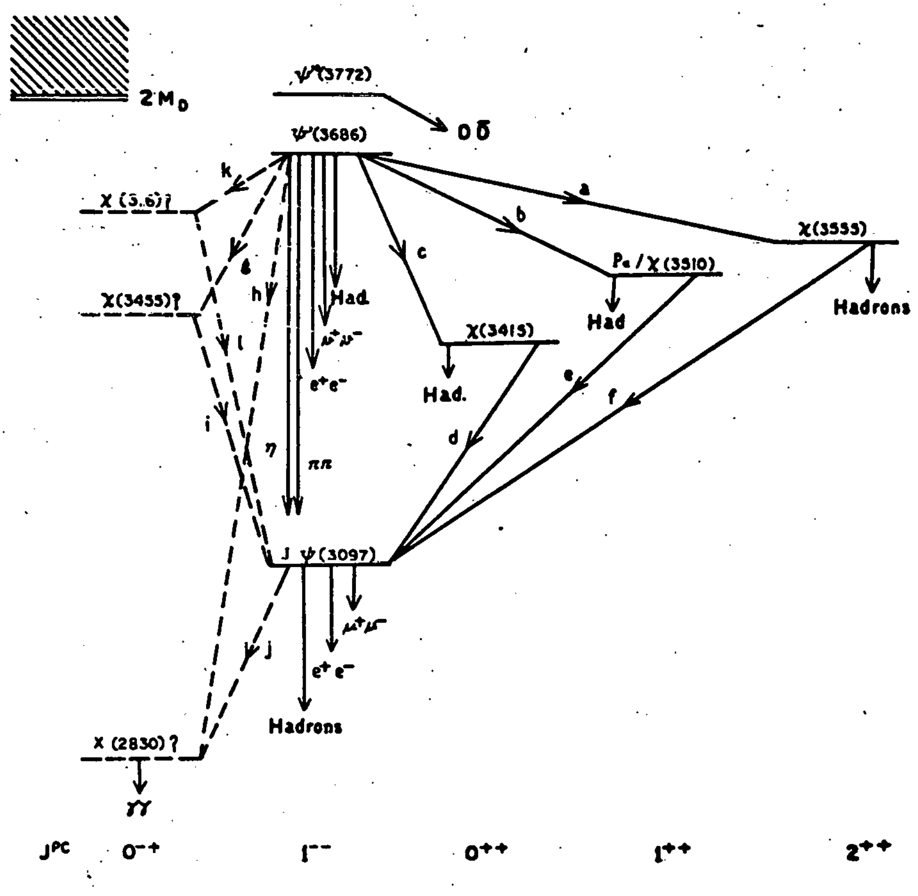
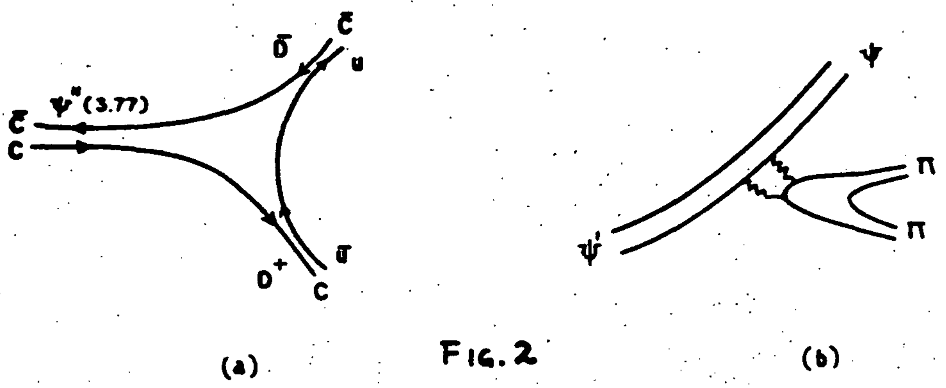
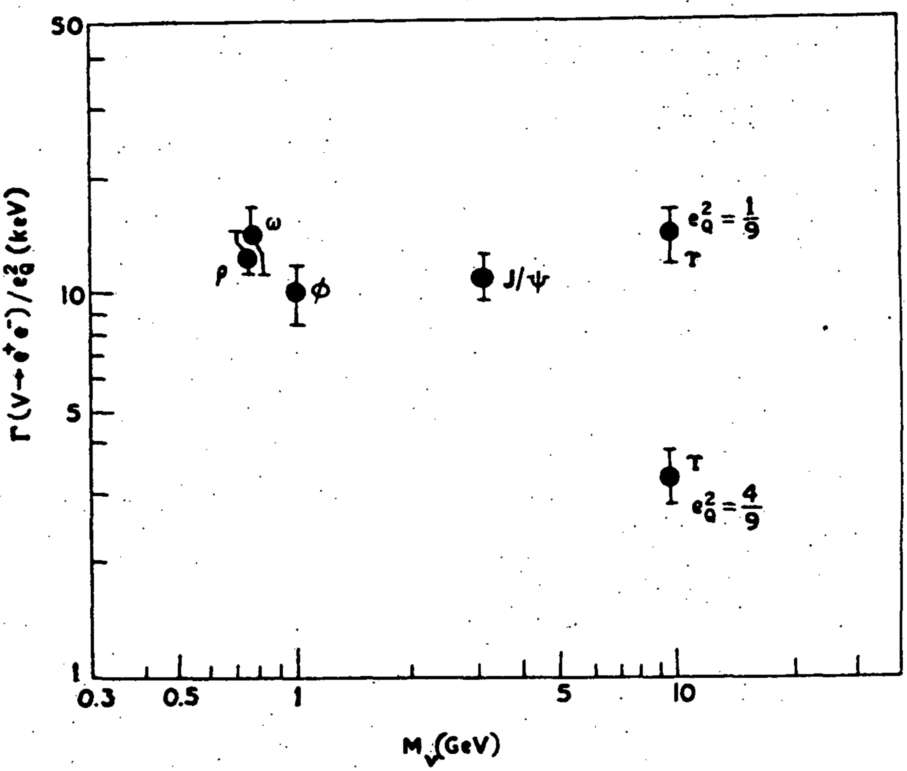

2 M_D
ψ''(3772)
DD̄
ψ'(3686)
X (3.6)?
X(3455)?
X(3415)
Pc / X(3510)
X(3555)
Had
Had.
Hadrons
μ+μ-
e+e-
ππ
η
J ψ(3097)
X (2830)?
γγ
a
b
c
d
e
f
g
h
i
j
k
l
J^PC 0-+ 1-- 0++ 1++ 2++

Fig. 1



c̄
c
ψ"(3.77)
D̄
c̄
u
ū
D+
c
ψ
π
π
ψ'
(a)
(b)

FIG. 2



50
10
5
1
0.3
0.5
1
5
10
ω
ρ
φ
J/ψ
$e_Q^2 = \frac{1}{9}$
Υ
Υ
$e_Q^2 = \frac{4}{9}$
$\Gamma(V \to e^+e^-)/e_Q^2$ (keV)
M_V(GeV)

Fig. 3

DISCUSSIONS

S.P. Misra : (i) When you take K = .4 to .45 and e.g. get correct splitting for ψ and η_c, still etc. puzzle of electromagnetic transitions remains.

(ii) For $B \frac{d\sigma}{dy}|_{\psi,\psi'}$ compared to $B \frac{d\sigma}{dy}|_{\Upsilon,\Upsilon',\Upsilon''}$ the ratios are probably different just because branching ratios are different. Can that be so?

A. Khare : Yes! You are quite right. The puzzle of M1 transition rates still remains.
Yes! As I mentioned in my talk probably it is because

$B(\Upsilon' \to \mu^+\mu^-) >> B(\psi' \to \mu^+\mu^-)$

S.R. Choudhury : 1. You said that the linear rather than logarithmic is more natural from the QCD point of view. Could you please elaborate on this.

2. You quoted the mass 5 GeV for the b-quark. But this in a contimued theory is just a parameter and is therefore model dependent. What is the stability of this figure 5 GeV?

A. Khare : 1. What I had said was that $V(r) = \frac{-4k}{3r} + ar$ is more natural than $(\log(\frac{r}{r_o}))$ from QCD point of view. From QCD we expect that at short distance the potential should go as $-1/r$. At long distance ofcourse the only requirement is of confinement and $V_c(r) = ar^\eta$ $o<\eta<r$ is as natural as $V_c(r) = ar$ (except that lattice gauge theory seems to suggest ar).

2. Certainly, m_b is a parameter in potential models. Number of calculations have been done in the literature and they seem to indicate that m_b lies between 3.5 and 5 GeV.

R. Ramachandran : 1) If χ(2.83) is baryonium, we should expect it to be even more narrow than in view of its double forbiddenness, a la OZI rule. Is there an experimental indication of this.

2) Is there a theoretical motivation for linear potential?

A. Khare : 1. Experimentally, I think, χ(2.83) appears to be broader than J/ψ.

2. There is no theoretical motivation for pure linear potential. However, from QCD there is definite motivation for $V(r) = -\frac{4k}{3r} + ar$.