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QUARKONIUM PHENOMENOLOGY

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Let me quickly stress the main experimental news in quarkonium.

- 1) There has been an absolute measurement of the mass of the upsilon at Novosibirsk which is : $M = 9.4596 \pm 0.0007$ GeV.
This measurement agrees with the DESY value. Consequently, the numbers I shall quote will be using this scale.
- 2) The first radial excitation of the P states of the upsilon system was observed at CESR by CUSB. The mass of the centre of gravity is : $M_{2p} = 10.247$ GeV.
The probable separation between the $J = 2$ and $J = 0$ states is of the order of 32 MeV.
- 3) We have, from Orsay, confirmation of the existence of the ϕ' .
- 4) The η'_c has been found by Crystal Ball, and $M_{\psi'} - M_{\eta'_c} \approx 92$ MeV.
 $M_{\eta'} - M_{\eta'_c} \approx 92$ MeV.
- 5) Radiative $E1$ and $M1$ branching ratios, as well as hadronic branching ratios have been obtained or confirmed.

There are two known approaches for describing theoretically the quarkonium system, i.e., $b\bar{b}$, $c\bar{c}$, and, with some daring, $s\bar{s}$, the potential approach and the QCD sum rules of the ITEP-Novosibirsk group. At this Conference "derivations" of a static potential for infinitely heavy quarks have also been proposed. Direct, lattice QCD calculations of *hadronic masses* are still in infancy.

The theoretical problems are :

- the mass spectrum
- leptonic widths
- hyperfine splittings
- fine structure
- E_1 transition rates
- M_1 transition rates
- hadronic decay rates (about which I shall not speak).

1. The Potential Models. - What are the *advantages* of the potential models? First of all their simplicity, their historical success in predicting the P states of $c\bar{c}$, the D states, the relative leptonic widths and their *ability* to predict high radial excitations. In particular, the number of narrow $\ell = 0$ states is correctly given by

$$n = \frac{1}{4} + \frac{2}{4} \sqrt{\frac{m_Q}{m_c}},$$

which even almost works for the $s\bar{s}$ system, since it gives $n \approx 1.1$. All good potentials agree in the range from 0.1 to 1 Fermi, which is relevant for $b\bar{b}$, $c\bar{c}$, and $s\bar{s}$ systems ¹⁾. The theoretical prejudice is that $V(r)$ behaves like $1/r \log(1/r)$ for $r \rightarrow 0$ and like r for $r \rightarrow \infty$. This is the case for a certain number of theoretically motivated potentials ²⁾ as well as certain potentials derived from QCD like the one of Adler and Pirani ³⁾ or of Stack (using SU_2 colour) ⁴⁾. On the other hand, I have proposed a simple phenomenological potential ⁵⁾

$$V = -8.064 + 6.870 r^{0.1}$$

with $m_b = 5.174$, $m_c = 1.8$, $m_s = 0.518$ (all units are powers of GeV's), which gives a good fit to the energy levels and the relative leptonic widths. The recently announced 2P state of the T system agrees with all potential models :

Theory	Experiment ⁷⁾
10.24 (Martin ⁵⁾)	
10.25 (Buchmüller et al. ²⁾)	10.247
10.27 (Cornell 1978 ⁶⁾)	

Quigg has noticed that if one tries to find directly what α is in $V = A + Br^\alpha$ from this new measurement, one gets

$$-0.25 < \alpha < +0.30$$

as shown on Fig. 1.

A distinction between various potentials comes from the comparison of the T and $J\psi$ leptonic widths. If one believes that the ratio $\Gamma_T^{ee}/\Gamma_{J\psi}^{ee}$ is given by the Weisskopf-Van Royen formula, Miller and Olsson ⁸⁾ point out that this favours a potential singular at the origin as opposed to a non-singular one. This is good since it agrees with QCD expectations. There are, of course, relativistic corrections which have been discussed in various contributions to this Conference ^{9), 10)}.

What are the problems of potential models that can be fixed up? The naive calculations of the E1 electromagnetic transition from ψ' to χ 's and from the χ 's to ϕ give partial widths which are, respectively, about 2 times and 1.5 times too large when compared with experiment. This problem cannot be solved by changing the potential because any good potential must reproduce the energy levels and the E1 matrix elements are constrained by exact sum rules ¹¹⁾. It is, basically, relativistic effects which reduce the magnitude of the matrix elements (the wave function shrinks towards the origin), and the $\psi' \rightarrow \chi$ matrix element, $\int U_\psi U_\chi r dr$, which contains a positive part for r large and a negative part for r small (the positive part wins ¹³⁾), is particularly unstable. These effects had already been

accounted for by a Bethe-Salpeter calculation of Henriques et al. ¹³⁾. A new estimation of relativistic effects by McClary and Byers ¹⁰⁾ reconciles theory and experiment. In the case of the recently observed transitions ⁷⁾ $\gamma'' \rightarrow \chi_b' \rightarrow \gamma'$ and $\gamma'' \rightarrow \chi_b' \rightarrow \gamma$, where quarks move much more slowly, the global rates are in accordance with expectations. However ¹⁰⁾, relativistic corrections are still important in the transitions involving the $J = 0$ states. The rates $\gamma'' \rightarrow \chi_b + \gamma$, very sensitive to the detailed shape of the potential, are difficult to predict.

A seemingly more serious problem is that of the M1 transition $J\psi \rightarrow \gamma\eta_c$. The experimental branching ratio is ¹⁴⁾

$$1.20^{+0.53}_{-0.35} \%$$

while the naïve theory

$$\Gamma(\psi \rightarrow \gamma\eta_c) = \frac{16}{27} \frac{\alpha}{(m_c)^2} \times "1"$$

leads to 2.5% with $m_c = 1.84$ GeV.

However, Sucher, Feinberg and Kang ^{15),16)} have pointed out that "1" should be replaced by

$$\frac{M_{J\psi} + (M_{\eta_c})^2}{2(M_{J\psi}^2)} \langle f | 1 - \frac{k^2 r^2}{24} - \frac{2p^2}{3m_c^2} - \frac{V_S}{m_c} | i \rangle$$

where V_S is the "scalar" part of the potential. Updating their figures, one gets :

- for $m_c = 1.8$

1% scalar confinement < branching ratio < 2% vector confinement

- for $m_c = 1.6$

1.3% scalar confinement < branching ratio < 2.7% vector confinement.

So there is no contradiction between theory and experiment. However, the theory does not make a strict prediction since nobody knows the exact amount of the presumably dominant scalar part of the confining potential.

One might worry that m_c could be much smaller than 1.6 MeV. We argue that the constituent mass cannot go below 1.5 GeV. There are good reasons to believe that the binding energy of a $Q\bar{Q}$ system becomes more negative when the quark mass increases. Therefore

$$m_c(\text{const}) > \frac{1}{2} \left[\frac{3}{4} m_{J\psi} + - m_{\eta_c} - \frac{3}{4} m_p - \frac{1}{4} m_\pi \right] + m_u \approx 1.5,$$

with the constituent quark mass $m_u = m_d = 0.3$ GeV.

We come now to the major criticisms of the potential approach. The main one is that the potential is *arbitrary*. However, we see that the central part has not much flexibility since all the predictions of the 2P state of the T system agree with each other and with experiment! Perhaps the most comforting news of this Conference is that, in a number of papers, Flory ¹⁷⁾, Soni and Tran ¹⁸⁾, Adler and Pirani ³⁾ and Stack ⁴⁾, show ways of deriving a static potential from QCD (lattice, analytic, or QCD sum rules) and this potential, for instance in Ref. 3), agrees with the phenomenological potential describing the heavy quark-antiquark spectrum and has a linear part in agreement with the Regge slope.

Perhaps the most violent criticism concerns the spin dependent part of the potential. It is a fact that when it was believed that the η_c had a mass 2.83 GeV, a few physicists tried to account for this by an ad hoc potential. However, the views of the majority were well expressed by Krasemann and Krammer, in Schlading in the winter of 1979 11):

"Up to now, we do not know any quarkonium pseudoscalar state definitely. The experimental candidates can hardly be understood. Especially, their M1 transitions and gluon annihilation properties should be much different from what is observed."

In fact, before the discovery of the true η_c , Beavis et al. 19) predicted a ψ - η_c mass difference of 84 MeV and, later on, Buchmüller et al. 2) got 99 MeV. From a fit to ψ - $\eta_c = 112$ MeV they predicted ψ' - $\eta_c' = 80 \pm 10$ MeV, to be compared with the experimental value of 92 MeV.

The comparison of ψ - η_c and ψ' - η_c' mass difference is very informative on the nature of the spin-spin forces. J.M. Richard and I 20) have shown that in the simple potential approach it favours a very short-range force, for instance a Fermi type term. However, problems arise if one tries to take into account the coupling to charmed meson pairs because the ψ' is much more affected than the η_c' by this coupling. However, the calculations exhibit a great instability with respect to parameters and it is not clear that we should be worried by the results of this too sophisticated model.

Concerning the fine structure, I can quote the results of Buchmüller 21) (see also Ono 22)) :

		Theory	Experiment
$c\bar{c}$	$\left\{ \begin{array}{l} {}^3P_2 \\ {}^3P_1 \\ {}^3P_0 \end{array} \right.$	3553 3502 3419	3551 MeV 3507 3414
$b\bar{b}$	$\left\{ \begin{array}{l} \chi_b \quad (J=2) - (J=0) = 72 \text{ to } 49 \text{ MeV} \\ \chi_b' \quad (J=2) - (J=0) = 56 \text{ to } 32 \text{ MeV,} \end{array} \right.$		

depending on α_s . For the (χ_b') 's states, experiment 7) seems to indicate an overall spacing of 31 MeV.

2. The QCD Sum Rules.- This very ingenious method, invented by the ITEP and Novosibirsk theorists 23) has the major advantage that it contains, in principle, very few parameters : α_s , current quark masses, magnitude of the gluon condensate.

The starting point is also more fundamental. However, the power of the method is limited to the prediction of the masses and properties of ground states ψ , η_c , χ_0 , χ_1 , χ_2 , T , η_b , χ_b , but not of the radial excitations.

The most spectacular success of the sum rules was the prediction $M_\psi - M_{\eta_c} \approx 100$ MeV by Shifman et al. A more recent achievement has been the prediction of the P state splittings by Reinders et al. 24) using power moments. However, Bertlmann 25), using exponential moments, does not get as spectacular a success:

	Experiment	Bertlmann	Reinders, Rubinstein and Yasuki
η_c	2.98	3.04	3.01
$J\psi$	3.10	3.10	3.10
χ_0	3.41	3.48	3.40
χ_1	3.51	3.52	3.50
χ_2	3.55	3.56	3.56

It is difficult to judge from the outside who is right. According to Broadhurst 26), the method might have some basic instability.

There is, however, a decisive and feasible test which is the measurement of the mass of the $1P$ state of the T system.

The predictions of the *QCD sum rules* for the centre of gravity of the P states are :

$$M_{\chi_b} = \begin{cases} 9.83 \pm 0.03 & (\text{Voloshin } 27)) \\ 9.80 \pm 0.01 & (\text{Bertlmann } 25)) \end{cases}$$

with presumably very small fine structure splittings (this should be checked!), while the potential models predict 9.86 (Martin 5), Buchmüller 2)) to 9.92 (Cornell 6)) GeV.

I should add that *QCD sum rules* give good predictions for the leptonic widths. The $E1$ and $M1$ transition rates are correct within a factor of $\frac{1}{2}$ to 2, but the calculations are subject to improvement 28).

Finally, I would like to give a list of predictions for the T - η_b mass difference:

- 60 MeV Reinders, Rubinstein, Yasuki (*QCD sum rules*) 24)
- 30 MeV Voloshin (*QCD sum rules*, confirmed)
- 60 MeV Martin (naïve potential, naïve Fermi term) 5)
- 30-40 MeV Buchmüller 29)
- 100 MeV McClary-Byers 10)

I want to finish with a prediction which results from a purely empirical observation. If we calculate $(m(J=1))^2 - (m(J=0))^2$, we find $m_D^2 - m_\pi^2 \cong m_{K^*}^2 - m_K^2 \cong m_{D^*}^2 - m_D^2 \cong 0.56 \text{ (GeV)}^2$, for systems containing *one light quark* (this is the old Gell-Mann - Zweig relation!). However, for a *heavier* reduced mass, $(M_{J\psi})^2 - (M_{\eta_c})^2 = 0.67 \text{ (GeV)}^2$ and I expect that this trend will continue for heavier quarks. From $M_T^2 - M_{\eta_b}^2 > 0.67$ we get $M_T - M_{\eta_b} > 36 \text{ MeV}$.

Apologies. - I apologize for not speaking on : - hadronic transitions and 2-3 gluon decays, - universal fits of mesons and baryons, which, in spite of their many parameters, are impressive.

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