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:
   \[ M = 9.4596 \pm 0.0007 \text{ GeV}. \]
   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:
   \[ M_{Zp} = 10.247 \text{ GeV}. \]
   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 \( \psi' \).

4) The \( \eta_c' \) has been found by Crystal Ball, and \( M_{\psi'} - M_{\eta_c} = 92 \text{ MeV} \).

5) Radiative El 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
- \( E1 \) transition rates
- \( M1 \) 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 \( R = 0 \) states is correctly given by
   \[ n = \frac{1}{6} + \frac{2}{7} \sqrt{\frac{M}{M_C}}, \]
which even almost works for the \( s \bar{s} \) system, since it gives \( n = 1.1 \). 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 \( r \to 0 \) and like \( r \) for \( r \to \infty \). 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 \( m_e = 5.174, m_u = 1.8, m_s = 0.518 \) (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:

<table>
<thead>
<tr>
<th>Theory</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.24 (Martin(^5))</td>
<td>10.247</td>
</tr>
<tr>
<td>10.25 (Buchmüller et al.(^2))</td>
<td>10.247</td>
</tr>
<tr>
<td>10.27 (Cornell 1978(^6))</td>
<td>10.247</td>
</tr>
</tbody>
</table>

Quigg has noticed that if one tries to find directly what \( \alpha \) 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 \( \Gamma_T^{2S+1} \Gamma_{J/\psi}^{1S+1} \) is given by the Weiskopf-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 El electromagnetic transition from \( \psi' \) to \( \chi' \)'s and from the \( \chi' \)'s to \( \phi \) 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 El 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 \( \psi' + \chi \) matrix element, \( \mathcal{M}_{\psi' \chi} \mathcal{M}_{\chi \psi} \mathcal{d}r \), 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 (14) reconciles theory and experiment. In the case of the recently observed transitions (7) \( \gamma'' + \chi_b + \gamma' \) and \( \gamma'' + \chi_b + \gamma_c \), 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 \( \gamma'' + \chi_b + \gamma_c \) very sensitive to the detailed shape of the potential, are difficult to predict.

A seemingly more serious problem is that of the M1 transition \( J\psi + \gamma n_c \). The experimental branching ratio is (14) 
\[
\frac{1.20 \pm 0.53}{0.39} \% 
\]
while the naïve theory
\[
\Gamma(\psi + \gamma n_c) = \frac{14}{27} \frac{\alpha}{(\pi)^2} \times n'' \times k^3 
\]
leads to 2.5% with \( m_c = 1.84 \) GeV.

However, Sucher, Feinberg and Kang (15,16) have pointed out that \( n'' \) should be replaced by
\[
\frac{n'' + (m_{n_c})^2}{2(n'' + 1)} \frac{f}{1 - \frac{m_{\psi}^2}{2n''}} - \frac{2p^2}{3m_c^2} \frac{V_s}{m_c} |1> 
\]
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

\[
m_c(const) > \frac{1}{3} \left[ \frac{3}{4} m_{\psi}^2 + m_{n_c} - \frac{1}{3} m_{p} - \frac{1}{3} m_{\bar{u}} \right] + m_u = 1.5, 
\]
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.
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Perhaps the most violent criticism concerns the spin dependent part of the potential. It is a fact that when it was believed that the $\eta_c$ had a mass $2.82$ 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 Schladming in the winter of 1979:

"Up to now, we do not know any quarkonium pseudoscalar state definitely. The experimental candidates can hardly be understood. Especially, their $M_1$ transitions and gluon annihilation properties should be much different from what is observed."

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

The comparison of $\psi-\eta_c$ and $\psi'-\eta_c$ 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 $\psi'$ is much more affected than the $\eta_c$ 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 $22)$):

<table>
<thead>
<tr>
<th>Theory</th>
<th>Experiment</th>
</tr>
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<tbody>
<tr>
<td>$3p^2$</td>
<td>3553</td>
</tr>
<tr>
<td>$3p^1$</td>
<td>3502</td>
</tr>
<tr>
<td>$3p_0$</td>
<td>3419</td>
</tr>
<tr>
<td>$X_{0}^\prime (J=0)$</td>
<td>3414</td>
</tr>
<tr>
<td>$X_0^\prime (J=2)$</td>
<td>49 MeV</td>
</tr>
<tr>
<td>$X_0^\prime (J=0)$</td>
<td>32 MeV</td>
</tr>
</tbody>
</table>

Xb $(J=2)$ to $(J=0)$ = 72 MeV to 49 MeV, depending on $\alpha_s$. For the $(X_0^\prime)^\prime$ states, experiment $7)$ seems to indicate an overall spacing of $\sim 31$ 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 : $\alpha_s$, 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 $\psi$, $\eta_c$, $\chi_0$, $\chi_1$, $\chi_2$, $\eta_b$, $X_b$, but not of the radial excitations.

The most spectacular success of the sum rules was the prediction $M_b - M_{X_b} \approx 100$ 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.
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:

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

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

I should add that QCD sum rules give good predictions for the leptonic widths. The $E_1$ and $M_1$ 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 $T-\eta_b$ mass difference:

- 60 MeV Reinders, Rubinstein, Yasuki (QCD sum rules) 24)
- 30 MeV Voloshin (QCD sum rules, confirmed)
- 60 MeV Martin (naive potential, naive 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 $(m(J=1) - m(J=0))^2$, we find $m_0^2 - m_2^2 = m_3^2 - m_1^2 \neq 0.56$ (GeV)$^2$, for systems containing one light quark (this is the old Gell-Mann - Zweig relation!). However, for a heavier reduced mass, $(m_{cb}^2 - m_{b}^2)^2 / (m_{bb}^2 - m_{b}^2) = 0.67$ (GeV)$^2$ and I expect that this trend will continue for heavier quarks. From $m_{T}^2 - m_{b}^2 > 0.67$ we get $m_{T} - m_{\eta_b} > 36$ 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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7) LEE FRANZINI J., Invited talk at this Conference. We have corrected the scale difference between CESR and the absolute measurement of Novosibirsk.
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9) IPO H., Preprint, Kinki University, Osaka, paper submitted to this Conference (0274).
14) BLOOM E., Rapporteur's talk at this Conference.
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23) Rather than giving the original references, we refer to the excellent review of SHIFMAN M.A., Proceedings of the 1981 International Lepton-Photon Symposium, Bonn, p. 242, W. Pfeil Editor (Universität Bonn, Physikalisches Institut).
26) BROADHURST D.J. and GENERALIS S., Preprint, The Open University, Milton Keynes, OUT-4102-8.