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Quarkonium and Hybrids - Experimental

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Abstract: A review is presented of the latest developments in the spectroscopy of heavy quarkonia, $c\bar{c}$ and $b\bar{b}$. Recent discoveries of $q\bar{q}g$ hybrids, as well as the emerging industry of applied quarkonia are also reviewed.

1. What is new with charmonium and bottomonium?

After a hiatus of more than 20 years, we now have two new and significant developments which are leading to a revived interest in the precision spectroscopy of $c\bar{c}$ charmonium. These are the successful exploitation of proton-antiproton annihilation in the $\sqrt{s} = 2.9 - 4.0$ GeV range at Fermilab (FNAL experiments E760, E835), and the BES spectrometer program at BEPC, the electron positron collider at Beijing. Both these experiments are providing high precision data for charmonium states, and are leading to much better understanding of QCD in the non-perturbative regime. I will discuss these developments in some detail.

Unfortunately, there are no corresponding developments in $b\bar{b}$ bottomonium spectroscopy. Proton - antiproton annihilation in the $\sqrt{s} = 9 - 11$ GeV has not been exploited (the required $\bar{p}$ storage rings in the momentum range 50 - 58 GeV do not exist), and the e^+e^- colliders in this $\sqrt{s}$ region have turned their attention to open charm, open beauty, and CP studies. As such, my review will contain very little new information (most of it comes from CLEO) on bottomonium physics.

The BES(BEPC) program [1] is modeled after the well known Mark III (SPEAR) program at SLAC. As such, all that needs to be said about it is that it has been successfully operating for 10 years, and that it has been churning out results based on a harvest of 9 million J/ψ and 3.8 million ψ'. I will discuss these also.

The Fermilab $p\bar{p}$ program became operative in 1990, and it has had two successful runs, E760 (1990-91) and its successor E835(1996-97). The next run is planned for the year 2000. Since the $p\bar{p}$ annihilation technique for the study of charmonium is new, let me describe it briefly [2].

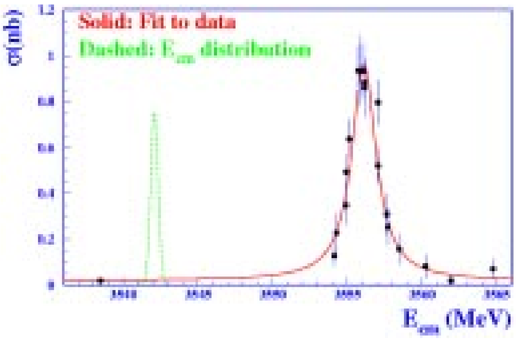

Figure 1: A typical resonance scan (χ_{c2}) in Fermilab E760/E835. The dashed peak represents the instrumental mass resolution function.

The Fermilab antiproton source was designed to produce, store, and cool antiprotons at 9 GeV in order to feed the Tevatron collider program. However, when the collider experiments are not running, it is possible to use the stored $\bar{p}$ in the accumulator ring for other experiments. The $\bar{p}$ can be decelerated effectively to any energy down to ≈ 3 GeV. A cluster jet target of hydrogen intersects the circulating beam in the accumulator ring, and the electromagnetic products of annihilation, photons and electrons, are detected in an azimuthally symmetric detector. Charmonium resonances are scanned by varying the antiproton energy in small steps, and unprecedented mass resolution (≈ 1 part in 10^4), and energy precision (≈ 1 part in 10^5), are realised. An illustrative scan, one for the χ_{c2} resonance [2], is shown in figure 1. The greatest advantage of $p\bar{p}$ annihilation is that it can form states of all J^{PC}, whereas e^+e^- annihilation can only directly form vector states.

2. Overview of the current status

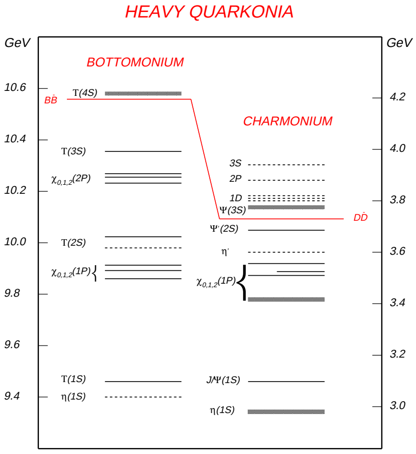

Figure 2: Spectra of bottomonium and charmonium

To put things in perspective, I show the spectra of charmonium and bottomonium in figure 2. In table 1, I have summarized the information that is available in PDG98 [3] about charmonium and bottomonium resonances. It is to be noted that except for J/ψ (for which 118 hadronic decay channels have been measured) most resonances have had less than 10 hadronic channels measured, and these account for less than $\approx 15\%$ of the total hadronic decay branching ratio. More than half the decays measured have errors larger than 30%. This is a regrettable state of affairs. E760 / 835 is not really equipped to measure hadronic decays, BES is making a valiant and lonely effort, but nothing more is happening. The study of QCD, and in particular, the understanding of hadronization, is being seriously compromised as a result.

3. Vector states of charmonium and bottomonium

Here, the post-1990 news is a large revision of the two most important parameters of charmonium physics - the total and e^+e^- widths of J/ψ and ψ'. For 25 years, these were:

$$\Gamma(J/\psi) = 68(10)\ \text{keV},$$
$$\Gamma(J/\psi \to e^+e^-) = 4.7(7)\ \text{keV},$$
$$\Gamma(\psi') = 243(43)\ \text{keV},$$
$$\Gamma(\psi' \to e^+e^-) = 2.1(3)\ \text{keV}, \qquad (1)$$

as obtained by indirect measurements (areas under peaks for e^+e^-, $\mu^+\mu^-$ and hadronic decays of J/ψ and ψ'). The Fermilab E760 experiment measured these widths directly [4] by scanning the resonances with their high resolution antiproton beam, and showed that the actual widths were as much as 45% larger.

$$\Gamma(J/\psi)9 = 99(13)\ \text{keV},$$
$$\Gamma(J/\psi \to e^+e^-) = 6.0(8)\ \text{keV},$$
$$\Gamma(\psi') = 306(50)\ \text{keV},$$
$$\Gamma(\psi' \to e^+e^-) = 2.6(5)\ \text{keV}. \qquad (2)$$

These new results are expected to have a large impact on many important phenomenological parameters of QCD. For example, the estimate of the vacuum expectation value of the gluon-condensate ($< G^2 > \equiv < 0|(\alpha_s/\pi)G_{\mu\nu}G_{\mu\nu}|0 >$) will increase by $\approx 30\%$.

As far as the Upsilon states, $\Upsilon(1S,\ 2S,\ 3S,\ 4S,\ 5S)$, are concerned, the last entries in PDG98 [3] date back to 1995. Since then, only two new measurements, both from CLEO, have been reported.

The first is a precision measurement of $\Upsilon(2S) \to \Upsilon(1S) + \pi\pi$. It gives the ratio $(\pi^+\pi^-)/(\pi^0\pi^0) = 2.09 \pm 0.13 \pm 0.17$, which constitutes an excellent confirmation of isospin conservation [5].

The second is a measurement of the direct photon spectrum of $\Upsilon(1S)$ decay, $\Upsilon(1S) \to \gamma + X$ [6]. As shown in figure 3, the data are in excellent agreement with the pQCD prediction, in marked contrast to the direct photon spectrum from J/ψ decay [7], shown in figure 4. It begins to appear more and more likely that the old J/ψ

	Number of Decay Channels				
$R_{c\bar{c}}$, $R_{b\bar{b}}$	Total	ϵ $\leq 15\%$	ϵ $\leq 30\%$	UL, or ϵ $\geq 30\%$	Hadronic BR seen (%)
η_c	19			19	26.1
J/ψ	118	36	42	40	51.6
ψ'	30	4	7	19	59.1
χ_{c0}	12		4	8	13.1
χ_{c1}	9	1		8	7.7
χ_{c2}	13	1	2	10	8.3
$^1P_1$	3			3	seen
$\psi(3770)$	2			2	dominant
$\psi(4040)$	6		1	5	seen
$\psi(4160)$	1			1	seen
$\psi(4415)$	2			2	seen
η_b	0				0
$\Upsilon(1S)$	5			5	1.2
$\Upsilon(2S)$	5	2		3	35.0
$\Upsilon(3S)$	4		4		16.6
$\Upsilon(4S)$	1	1			96
$\chi_{bJ}(1P)$					0
$\chi_{bJ}(2P)$					0

Table 1: Summary of available data on hadronic decays of charmonium, $c\bar{c}$, and bottomonium, $b\bar{b}$, states. [3]

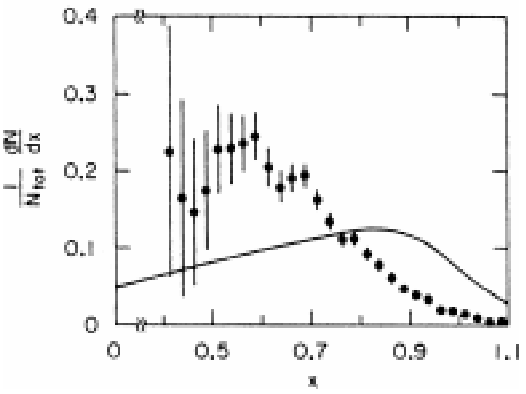

Figure 3: Direct photon spectrum for J/ψ; $x_\gamma \equiv E_\gamma/E_{beam}$.

measurement has problems. This measurement needs to be repeated, and I hope BES will make it a high priority.

3.1 The unbound vector states

It is worth noticing that almost nothing beyond the e^+e^- branching ratios is known about the higher vector states $\psi^{(3)}$, $\psi^{(4)}$, $\psi^{(5)}$, $\psi^{(6)}$, ... And, what is known appears to be highly suspect. For example, $B(\psi^{(n)} \to e^+e^-)$ for all these unbound vector states is stated to be $\approx 1.0 \times 10^{-5}$, on the basis of ~ 1978 measurements. In case of the corresponding unbound vector states of bottomonium, $B(\Upsilon^{(n)} \to e^+e^-)$ is found to decrease by an order of magnitude in going from the unbound $\Upsilon(4S)$ to $\Upsilon(5S)$.

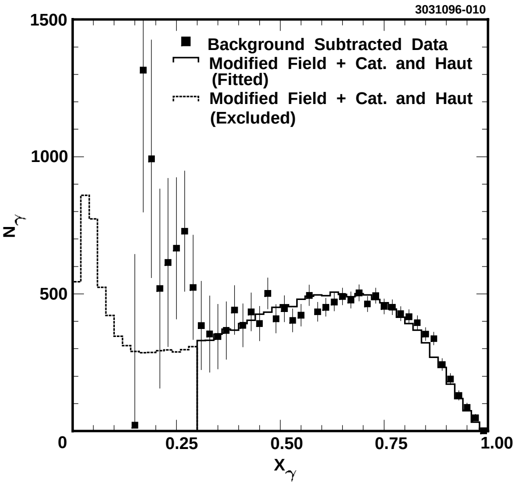

Figure 4: Direct photon spectrum for $\Upsilon(1S)$; $x_\gamma \equiv E_\gamma/E_{beam}$.

It is also worth reminding ourselves that ever since 1978, when the peculiar decay ratios

$$\psi(4040) \to D^0\bar{D}^0 : \bar{D}^0D^* : D^*\bar{D}^* = 1 : 20(11) : 640(380) \qquad (3)$$

were reported (as opposed to the naive expectation of $1:\ 4:\ 7$), theorists have been overexerting their imaginations to explain these results. We owe it to them to measure these ratios more reliably, and to prove or disprove the conjectures which range from D^*D^* molecules to dramatic consequences of nodal structures of wave functions.

3.2 The $\rho-\pi$ problem of charmonium

According to pQCD, because both $^3S_1 \to \gamma \to e^+e^-$ and $^3S_1 \to ggg \to hadrons$ decays are proportional to $|\psi(0)|^2$, the ratio

$$\begin{aligned} R \equiv B(\psi' \to e^+e^-)/B(J/\psi \to e^+e^-) &= 0.14(1) \\ = B(\psi' \to h)/B(\psi \to h)& \\ = B(\psi' \to h_i)/B(\psi \to h_i)& \end{aligned} \tag{4}$$

[Note that the last equality implies the questionable assumption that there is no differential physics involved in $h = \sum_i h_i$ versus h_i.]

It was noted many years ago, that the vector-pseudoscalar decay, $h_i = \rho + \pi$, which is one of the strongest hadronic decay channels for J/ψ ($B(J/\psi \to \rho\pi) = 1.3(1)\%$), strongly violates the expectation of equation 4, and $R(\rho\pi) < 2\times10^{-3}$. This '$\rho-\pi$ problem' received great theoretical attention, and explanations ranging from hidden glueballs [8], to intrinsic charm [9], to color octet enhancement [10], have been offered over the last fifteen years. BES has measured a large number of ψ' and J/ψ decays to delineate the nature of this problem [11]. The results are illustrated in figure 5.

None of the explanations offered so far are able to explain these observations, but I wish to note one rather clear systematic. The multiparticle decay channels illustrated in the top part of figure 5 all appear to obey the $R = 14\%$ expectation, while the two particle decay channels in the bottom part of figure 5 exhibit large variations. Speaking rather naively, it appears to me that this is as it should be. The multiparticle decays should more closely mirror the behavior of the total hadronic decays, while each individual two-particle decay should contain its own physics.

4. Triplet P-states

Since P-states are not directly formed in e^+e^- annihilation, their widths could not be measured prior to Fermilab E760/E835. By measuring the widths of $^3P_{0,1,2}$ states with precision [12] [13], this experiment has made it possible to do detailed spectroscopy of the $l = 1$ states of charmonium. Among the notable results are the following.

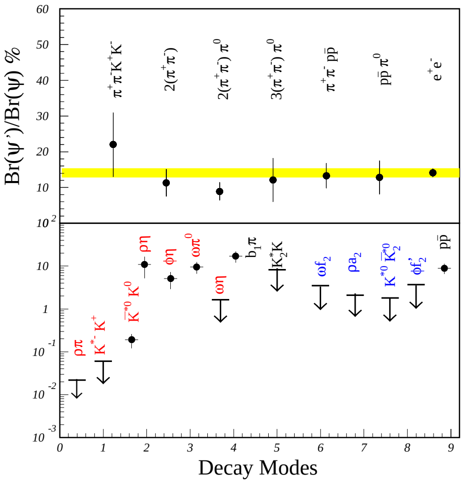

Figure 5: Ratios of hadronic decay widths of ψ' and J/ψ.

4.1 Two photon widths

The two photon width of the χ_{c2} resonance has been measured in the reaction $p\bar{p} \to \chi_{c2} \to \gamma\gamma$ with good precision, with the result $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.34(7)$ keV. This represents great improvement over photon - photon fusion measurements by CLEO [14], OPAL [15], and L3 [16], all of which continue to suffer from poor statistics and poor signal to background ratio.

4.2 Hyperfine splitting

As is well known, the Lorentz character of the confinement part of the $q\bar{q}$ potential is not well established. The informed prejudice is that the confinement part is scalar. This predicts that the fine structure splitting of the P-states, as measured by $R \equiv (M(^3P_2) - M(^3P_1))/(M(^3P_1) - M(^3P_0))$ should be such that $R(\chi_c) > R(\chi_{b'}) > R(\chi_b)$. Unfortunately, the experimental results were exactly opposite, $R(\chi_c) = 0.48(1)$, $R(\chi_{b'}) = 0.58(1)$, $R(\chi_b) = 0.65(13)$. A new measurement by CLEO [17] has solved half of the problem. It reports the much improved result $R(\chi_b) = 0.54(3)$, so that now $R(\chi_{b'}) > R(\chi_b)$. The problem with $R(\chi_c)$ remains. It most likely arises from relativistic effects.

4.3 The hadronic widths of χ_{c0} and χ_{c2}

According to the lowest order pQCD, the total hadronic widths of χ_{c0} and χ_{c2} have identical dependences on the derivative of the wave function at the origin, and on the c quark mass. These cancel in the ratios, so that $\Gamma(\chi_{c0} \to h)/\Gamma(\chi_{c2} \to h) = 15/4$. When one-loop radiative corrections are taken into account, the expected ratio of total hadronic widths becomes = 9.7. Recently, E835 [13] and BES [18] have measured a number of hadronic widths for χ_{c0} and χ_{c2}. The measured ratios $\Gamma(\chi_{c0} \to h_i)/\Gamma(\chi_{c2} \to h_i)$ are shown in figure 6. We note that for the multiparticle decay channels, the measured ratios are indeed very close to the expected 9.7. However, for two body decays the ratios are larger and show considerable variation. The situation is very similar to that noted for the ratio $\Gamma(\psi' \to h_i)/\Gamma(J/\psi \to h_i)$ in Sec. 3.2, and our explanation for it is the same. Multiparticle decays mirror the total hadronic decays, two-body decays do not - they have their characteristic physics.

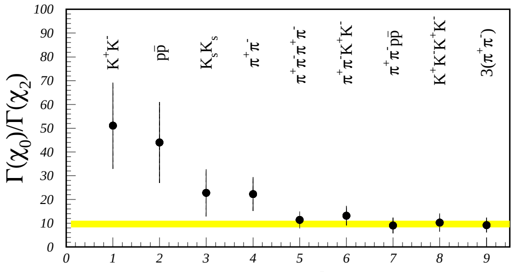

Figure 6: Experimental ratios of corresponding hadronic widths of χ_{c0} and χ_{c2} [13] [18].

5. Spin singlet states

These are generally the most difficult states to access and study. This is because in e^+e^- annihilation it is the spin triplet vector states (J/ψ, ψ', Υ, ...) which are directly formed. Their radiative decay to spin singlet states, $^1S_0(\eta_c, \eta_b)$, is M1 and therefore highly suppressed. In other cases, e.g. $^1P_1(h_c)$, the radiative decay is entirely forbidden by C-conservation. The result is that no singlet state has ever been identified in bottomonium, and only one singlet state, η_c, was identified in charmonium.

5.1 Singlet S-states

In e^+e^- experiments, singlet $^1S_0$ states can only be formed by $M1$ radiative transitions from $^3S_1$ states, either allowed ($1^3S_1 \to 1^1S_0\gamma$) or 'hindered' ($2^3S_1 \to 1^1S_0\gamma$). These transitions are a factor $(2m_b/m_c)^2 \approx 30$ weaker in bottomonium than the corresponding transitions in charmonium, making it extremely difficult to identify η_b. Further, note that it took 1.8 million ψ' and 2.2 million J/ψ to identify η_c definitively [19] in the Crystal Ball measurements; the best of $\Upsilon(1S)$ and $\Upsilon(2S)$ measurements [20] are only able to field an order of magnitude smaller numbers of $\Upsilon(1S)$ and $\Upsilon(2S)$. The result is that we do not have any information about the ground state of the $b\bar{b}$ system. This is most unfortunate.

The situation is better, perhaps not much, for η_c, the ground state of the $c\bar{c}$ system. The resonance has been unambiguously identified [3] [19], but none of its 19 hadronic decay channels have been measured with better than 30% errors; half of them have only upper limits established. Only one radiative decay, $\eta_c \to \gamma\gamma$, has ever been measured, and it is here that we have some progress to report. Prior measurements of this decay have been via photon-photon fusion, $e^+e^- \to e^+e^- + (\gamma\gamma)_{\eta_c}$. These measurements have the theoretical advantage that the cross section is directly proportional to $\Gamma_{\gamma\gamma}$, but they suffer from several serious experimental disadvantages, viz., unfavourable signal to background, and poor statistics spread over the identification of several hadronic decay channels of η_c. The result is that the deduced widths range from $\Gamma_{\gamma\gamma} = 4.3 \pm 1.9$ keV (CLEO [14]) to $\Gamma_{\gamma\gamma} = 11.3 \pm 4.2$ keV (ARGUS [21]).

A notable development is the recent measurement of $\Gamma_{\gamma\gamma}(\eta_c)$ by E760/E835. The E835

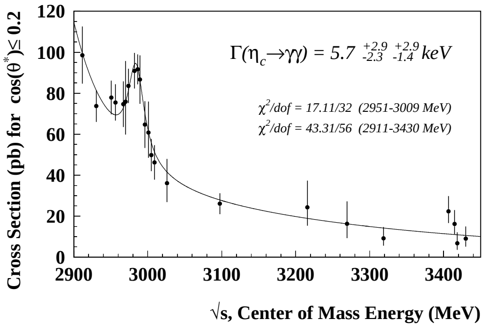

Figure 7: Scan results for $p\bar{p} \to \eta_c \to \gamma\gamma$ from E835 [22].

measurement is illustrated in figure 7 [22]. While statistics is much less of a problem here, backgrounds continue to plague these measurements as well. Further, the quantity measured here is the product $B(p\bar{p} \to \eta_c) \times B(\eta_c \to \gamma\gamma)$, so that the $\sim$ 30% uncertainty in $B(p\bar{p} \to \eta_c)$ [21] and the uncertainty in the total width, $\Gamma(\eta_c)$, lead to a rather large systematic error, $\Gamma_{\gamma\gamma}(\eta_c) = 5.7^{+2.9+2.9}_{-2.3-1.4}$ keV. [22] Needless to say, better measurements are needed.

The radial excitation of η_c, the $\eta_c'(2^1P_0)$ has been difficult to find. Crystal Ball at SLAC claimed to have found it, but no other experiment has succeeded in confirming it. E760 and E835 both looked for it, because it was expected that its two photon width should be comparable to that of η_c, with $(\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c) = 0.5-0.8)$. The result of the E835 search is that no evidence for η_c' can be found in the mass range 3584-3624 MeV, and that the upper limit for its product branching ratio is a factor 4-8 smaller than the level at which η_c has been observed [22]. This result is extremely surprising.

The E835 result does not tell us which one of the branching ratios $B(p\bar{p} \to \eta_c)$, or $B(\eta_c \to \gamma\gamma)$ is responsible for the unexpected quenching of η_c'. Since the photon - photon fusion measurements, $e^+e^- \to e^+e^- + (\gamma\gamma)_{\eta_c}$ yield $\Gamma_{\gamma\gamma}$ directly, we have looked for η_c and η_c' in the DELPHI data [23]. As shown in figure 8, no evidence is found in these data, either. DELPHI finds

$$\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c) = 0.03 \pm 0.03 \pm 0.16$$

This result has further deepened the mystery of the missing η_c'.

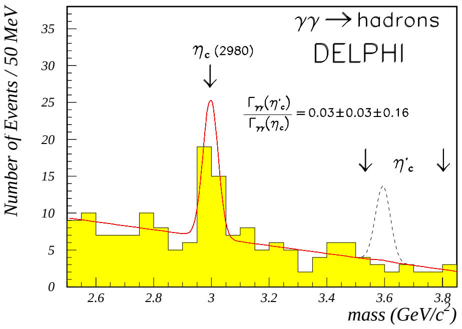

Figure 8: Results for $\gamma\gamma$ fusion from DELPHI [23]. The peak drawn at $M \approx 3.6$ GeV is to show what is expected for η_c' according to theoretical calculations.

5.2 Singlet P-state

E760 had earlier reported [24] the identification of the $^1P_1$ resonance of charmonium. Its measured mass differed from that of the centroid of ^3P_J states by 0.93 ± 0.25 MeV. This result indicates that there is a definite spin-dependent component in the confinement potential, but that it is reassuringly small. E835p, expected to run in early 2000, intends to study this state in detail, and to measure its width and branching ratios.

6. The strong coupling constant

The best way to determine the strong coupling constant α_s from charmonium and bottomonium decays is to form ratios of two branching ratios, chosen so that their dependences on the unknown quark masses and wave functions (or their derivatives) at the origin cancel out. Unfortunately, when this is done by forming the ratios of J/ψ and Υ hadronic widths and their e^+e^- widths, the results are known to be anomalously small:
$\alpha_s[(J/\psi \to ggg)/(J/\psi \to e^+e^-)] = 0.192(6)$,
$\alpha_s[(\Upsilon \to ggg)/(\Upsilon \to e^+e^-)] = 0.172(2)$.
[To wit, α_s determined by τ decay is known to be $= 0.34(2)$, and $m_\tau = 1.78$ GeV and $m_c \approx 1.5$ GeV are very close.]

Many attempts have been made to understand these results, and the two most cited culprits seem to be relativistic effects, and the dissimilarity between the annihilation vertices, $V \to ggg$, and $V \to \gamma \to e^+e^-$ [25].

Fortunately, with the new measurements of $\Gamma(gg)$ and $\Gamma(\gamma\gamma)$ for both η_c and χ_2 resonances, it has become possible to obtain rather reliable values of α_s at the charm quark mass. The results are:

$\alpha_s[(\eta_c \to gg)/(\eta_c \to \gamma\gamma)] = 0.32(5)$;

$\alpha_s[(\chi_2 \to gg)/(\chi_2 \to \gamma\gamma)] = 0.36(2)$

The average, $\alpha_s(m_c) = 0.35(2)$, extrapolates to $\alpha_s(m_Z) = 0.119(7)(7)$, which is in excellent agreement with the world average $\alpha_s(m_Z) = 0.119(2)$ (see figure 9).

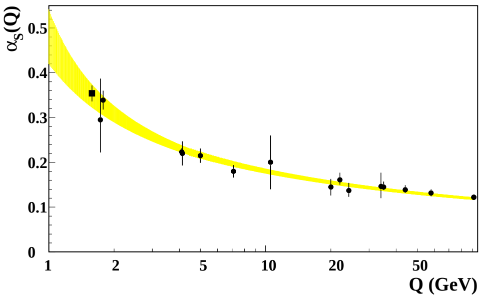

Figure 9: World data for the strong coupling constant [3] and the new result (square symbol) based on χ_{c2} and η_c from E835 [22].

7. Exotic Mesons

Exotic mesons have become the talk of the town recently. These $B = 0$ color singlets can be $(q\bar{q}g)$ hybrids, or $(q\bar{q}q\bar{q})$ four-quark states. A number of lattice calculations of $(q\bar{q}g)$ hybrids have been made recently, and a number of experiments have reported observing them.

Most lattice calculations predict the masses of the lowest lying hybrids to be: $M(n\bar{n}g) = 1.8 - 2.0$ GeV $(n = u, d)$, $M(s\bar{s}g) = 2.1 - 2.2$ GeV, $M(c\bar{c}g) = 4.1 - 4.3$ GeV, and $M(b\bar{b}g) = 10.6 - 11.1$ GeV.

The recent experimental activity concerns the $(n\bar{n}g)$ hybrids. The strategy has been to look for 1^{-+} states which are forbidden for the normal $(q\bar{q})$ mesons, which must have $P = (-1)^{L+1}$, $C = (-1)^{L+S}$.

The first unambiguous claim for a 1^{-+} exotic was made recently by the Brookhaven experiment E852 [26]. They studied the reaction

$\pi^- p \to p(\eta\pi^-)$ at 18 GeV/c

and identified a 1^{-+} state with

$M(1^{-+}) = 1370 \pm 16$ MeV,

$\Gamma(1^{-+}) = 385 \pm 40$ MeV,

by careful partial wave analysis. Unambiguous evidence for the state came from three observations: a pronounced asymmetry in the angular distribution of $M(\eta\pi)$ in the 1.22-1.42 GeV range which is dominated by $a_2(1320)$, a peak in the $1^{-+}(P_+$ wave) intensity, and a phase difference between the D_+ wave (a_2) and the P_+ wave. The observation was confirmed very soon after by a completely different experiment at LEAR (CERN), $\bar{p}d \to p + n\pi^-\pi^0$. A Dalitz plot analysis of the data yielded the result [27]

$M(1^{-+}) = 1400 \pm 30$ MeV,

$\Gamma(1^{-+}) = 310 \pm 70$ MeV.

The discovery of the 1^{-+} hybrid was not greeted by the theorists with glee, as one might have hoped. They had predicted the hybrid 1^{-+}, but with 400-600 MeV larger mass. Should this discourage us? Actually, no!

It is true that most lattice calculations predict $M(1^{-+}) \approx 1800$ MeV, but it is also true that if one extrapolates the lattice predictions for the mass splitting $m(g) \equiv m(q\bar{q}g, 1^{-+}) - m(q\bar{q}, 1S)$ for the heavier b, c, and s quarks (for which the lattice calculations ought to be more reliable) to the $n = u, d$ quarks, one obtains the effective constituent gluon mass of $m(g) \approx 1.1$ GeV. This is shown in figure 10. Such an extrapolation would lead to the predicted mass $M(1^{-+}) \approx 1500$ MeV. Besides, to quote from a recent review of lattice calculations "knowing its (quenched QCD's) limitations should give us greater confidence in using it as a phenomenological model for quantities where $10 - 20\%$ accuracy is useful." [28]

Since the original discovery, the same E852 Collaboration, of which I am a part, has announced [29] the discovery of a second 1^{-+} resonance in the reaction

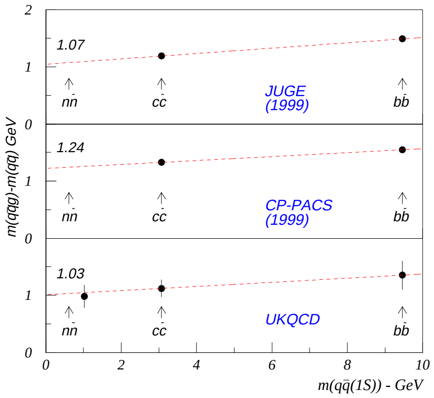

Figure 10: Lattice predictions for the mass splitting, $m(g) \equiv m(q\bar{q}g) - m(q\bar{q}, 1S)$.

$$\pi^- p \to p(\rho^0\pi^-), \quad \rho^0 \to \pi^+\pi^-,$$

with

$$M(1^{-+}) = 1593 \pm 8^{+29}_{-47} \text{ MeV},$$
$$\Gamma(1^{-+}) = 168 \pm 20^{+150}_{-12} \text{ MeV}.$$

This 1^{-+} state is also observed in the channel

$$\pi^- p \to p(\eta'\pi^-), \quad \eta' \to \eta\pi^+\pi^-.$$

It is clear that not only the first 1^{-+} $(q\bar{q}g)$ hybrid has been discovered, but a whole family of these exotic objects is at long last emerging from the forest. The theorists have a lot of explaining to do! For more details on these discoveries see review in Ref [30].

8. Glueballs

If the $(q\bar{q}g)$ hybrids are exotic, (gg, ggg) glueballs are more so. They are the unique predictions of the non-Abelian field theory of QCD. Unfortunately, I have neither the time, nor the place, nor the mandate, to discuss them here. I will simply tell you that we now have two viable candidates, $f_0(1500)$ and $f_0(1710)$, for the scalar (0^{++}) glueball, and the much talked about candidate for the tensor (2^{++}) glueball, the $\xi(2230)$, appears to be evaporating. For more on this fascinating story, I refer you to Ref [31].

9. Applied Quarkonium

Because they are the largest mass resonances which are rather copiously produced in all kinds of inclusive reactions, J/ψ and ψ' have become very important as 'diagnostic tools' for various phenomena. Their production has been studied at CDF/D0, HERA (H1/ZEUS), and in nuclear experiments at Fermilab (E866), and CERN (NA 38, NA50, NA51).

At the Tevatron, CDF had measured [32] the production of J/ψ and ψ' in $p\bar{p}$ collisions at $\sqrt{s} =$ 1.8 TeV, and reported an unexpectedly "large excess ($\sim$ a factor 50) of direct ψ' production compared with predictions from the color-singlet model". The result was confirmed by D0 [33]. It was claimed by CDF that both J/ψ and ψ' cross sections over a range of $p_T \approx 5 - 18$ GeV/c could be fit by adding an appropriate amount of color-octet contribution [34] from ${}^3S_1$, ${}^1S_0$, and ${}^3P_0$ states. The color-octet model also predicts that both J/ψ and ψ' should be produced with substantial transverse polarization (especially at high p_T). In a preliminary report, CDF finds that the polarization is consistant with zero at all p_T, casting serious doubt on the earlier explanation of production cross sections in terms of a dominant color-octet contribution.

At HERA, both ZEUS and H1 have made extensive measurements of elastic and inelastic photoproduction and electroproduction of J/ψ, ψ', and Υ. I cannot do justice to this body of work here, except to give the latest references [36] [37], and to state that much like CDF and D0, these measurements also find an overproduction of J/ψ and ψ', and they also conclude that inclusion of color-octet contributions does not explain the data.

The last item of applied quarkonium physics which I want to mention relates to J/ψ and ψ' attenuation in nuclei. As is well known, it has been conjectured that this suppression can be used as a signature for quark-gluon plasma (QGP) formation in heavy-ion collisions. J/ψ and ψ' suppression has been observed in p-nucleus collisions as well as ion-ion collisions. The important question is whether the observed attenuation can be explained entirely in terms of normal, or 'Glauber' attenuation, or if it is necessary to invoke QGP formation. No consensus on this question has been reached so far, although there is considerable speculation that the recent observations by NA50 in Pb-Pb collisions can not be explained by Glauber attenuation, and that they require QGP based explanations. The relevant data come from Refs [38] [39] [40].

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