The status of some of the recently discovered heavy hadrons is presented.

1. Introduction

More than 30 years after the November Revolution, charmonium spectroscopy continues to surprise and challenge. A new era began in April of 2003 when BaBar announced the discovery of the enigmatic $D_s(2317)$. This state continues to perplex us and Fermilab, CLEO, BES, BaBar, and Belle continue to add grist to the mill. This conference report is a brief review of the new heavy hadron spectroscopy.

2. The New States

2.1. $B_c$

CDF recently announced the discovery of the $B_c$ meson. The timing was arranged with the FNAL lattice group to permit them a prediction of its mass. The respective results are $6287(5)(1)$ MeV$^1$ and $6304(4)$ MeV$^2$. Thus CDF may claim a state, the lattice may claim a victory, and the $B_c$ appears to carry no surprises. Historians may be interested to know, however, that Godfrey and Isgur$^3$ predicted this mass with the same accuracy as the lattice, but with a twenty year lead time.

2.2. $h_c$

The $h_c$ has been observed by CLEO$^4$ with a mass of $3524(1)$ MeV. This may be compared with typical quark model expectations$^5$ of $3518$ MeV, leading one to suspect that the $h_c$ is also not hiding anything from us. Nevertheless, it tells us something: the $h_c$ lies within $2$ MeV of the spin-averaged mass of the $\chi_{cJ}$ multiplet: $M_{c.o.g.} = \frac{1}{9}(\chi_0 + 5\chi_1 + 9\chi_2) = 3525.36$. Since the splittings between these states are driven by the $O(v/c)$ quark interactions, we are learning something about the Dirac structure of confinement (namely that it is an effective scalar).
2.3. $\eta_c'$

The CLEO collaboration has observed the $\eta_c'$ with a mass of 3638(4) MeV and a width of 19(10) MeV. This is to be compared with the old result of Crystal Ball of 3592(5) MeV. The $\eta_c'$ is of some interest because its splitting with the $\psi'$ is driven by the hyperfine interaction and hence probes this interaction in a new region. Specifically, the ground state vector-pseudoscalar splitting is $m(J/\psi) - m(\eta_c) = 117$ MeV whereas the excited splitting is now measured to be $m(\psi') - m(\eta_c') = 48$ MeV.

Theoretical expectations for the former range from 108 to 123 MeV in simple (or ‘relativised’) quark models and thus are within expectations. Alternatively, the latter is predicted to be 67 MeV in the quark model of Eichten, Lane, and Quigg. However, the authors note that including unquenching effects due to open charm meson loops lowers this splitting to 46 MeV which is taken as evidence in favour of their ‘unquenched’ quark model. However, the simple quark models mentioned above find splittings of 42 - 53 MeV, indicating that it is too early to make definitive conclusions about loop effects. It is worth noting, furthermore, that attempts to unquench the quark model are fraught with technical difficulty and a great deal of effort is required before we can be confident in the results of any model.

2.4. $D_s(2317)$ and $D_s(2460)$

These states are roughly 100 MeV below quark model expectations and point to either exotic structure, such as $DK$ molecules, or to a deep misunderstanding of heavy-light hadrons. For example, the $DK$ and $D^*K$ continua are both nearby and couple to $D_{s0}$ and $D_{s1}$ in S-wave. Is it possible that we have underestimated the importance of coupled channel effects in some systems?

2.5. $D_s(2632)$

The $D_s(2632)$ was discovered by the SELEX collaboration at FNAL in the final states $D^0K^+$ and $D_s\eta$. The measured mass is 2632.6(1.6) MeV and the state is surprisingly narrow with a width of less than 17 MeV at the 90% confidence level. The ratio of the partial widths is measured to be

$$\frac{\Gamma(D_s \rightarrow D^0 K^+)}{\Gamma(D_s \rightarrow D_s \eta)} = 0.16 \pm 0.06.$$  \hspace{1cm} (1)

As pointed out by the SELEX collaboration, this is an unusual result since the $DK$ mode is favoured by phase space.

It is unlikely that this state is a $c\bar{s}$ hybrid since the mass of such a state is expected to be roughly 3170 MeV. Possible molecular states include a $D^*_s\eta$ system at 2660 MeV or $D^*_s\omega$ or $D^*K^+$ states at 2900 MeV. However the former is a P-wave which is not favoured for binding, while the latter are too heavy to be plausible.

The remaining possibility is that the $D_s(2632)$ is a radially excited $c\bar{s}$ vector (although it is some 100 MeV lighter than quark model predictions of 2730 MeV).
The peculiar decay ratio remains to be explained. Experience with the decay modes of the $\psi(3S)$ to $DD$, $DD^*$ and $D^*D^*$ points to a possible resolution: transition matrix elements for excited hadrons may have zeroes due to wavefunction nodes. It is possible that such a node is suppressing the $DK$ decay mode. Computation reveals that there is indeed a node but that it occurs at a wavefunction scale which is 20% lower than preferred. Furthermore, the $DK$ mode is always larger than the $D_s\eta$ mode.

We have run out of options and must conclude that the $D_s(2632)$ is an experimental artefact. This conclusion now appears likely because searches by FOCUS, BaBar, and CLEO have found no evidence for the state.

### 2.6. $X(3872)$

The $X(3872)$ is the poster boy of the new heavy hadrons – it has been confirmed by four experiments at a mass of 3872 MeV and is very narrow, $\Gamma < 2.3$ MeV at 95%. The anomalous nature of the $X$ has led to much speculation: tetraquark, cusp, hybrid, or glueball. But the most popular explanation is that it is a $DD^*$ bound state. This model has successfully predicted the quantum numbers of the $X$ ($J^{PC} = 1^{++}$), the decay mode $\pi\pi\pi J/\psi$, that the $\pi\pi$ and $3\pi$ modes should be comparable, and that the $\pi\pi$ invariant mass distribution should be dominated by the $\rho$ while the $3\pi$ invariant mass distribution should be dominated by the $\omega$.

This string of successes has met with recent experimental challenges: (i) The $X$ has been observed decaying to $\gamma J/\psi$ with a strength $Br(X \rightarrow \gamma J/\psi)/Br(X \rightarrow \pi\pi J/\psi) = 0.14(5)$. This rate is substantially larger than predicted in the model of Ref. 24. (ii) There are rumours that Belle have seen the mode $X \rightarrow D\bar{D}\pi$ and that its rate is ten times larger than that of $\pi\pi J/\psi$. The model predicts this ratio to be 1/20. (iii) BaBar reports $Br(B^0 \rightarrow X K^0)/Br(B^+ \rightarrow X K^+) = 0.61(36)$. This is at odds with the molecular picture which predicts a ratio of $O(\frac{1}{N_{c^2}}) + O(\frac{Z_{D^0} Z_{D^+}}{N_{c^2}}) \approx 10\%$. (iv) Belle and BaBar have measured the product of branching ratios:

$$Br(B^+ \rightarrow X K^+)Br(X \rightarrow \pi\pi J/\psi) = 1.3(3)[0.85(30)] \cdot 10^{-5}. \quad (3)$$

The new $D\bar{D}\pi$ data imply that $Br(B \rightarrow \pi\pi J/\psi) < 0.1$ which implies that $Br(B \rightarrow X K) > 10^{-4}$. This is comparable to the rate $Br(B \rightarrow \chi_{c1} K)$ and points to a large $c\bar{c}$ component in the $X$.

All of these new data may be accounted for if the predicted hidden charm interactions of Ref. 24 were over-estimated. This leads to weaker binding which gives rise to a much narrower $X$ with a dominant $D\bar{D}\pi$ mode, weak $\pi\pi J/\psi$ and $\pi\pi\pi J/\psi$ modes, and a radiative transition of the desired magnitude.
2.7. X (3940)

The X (3940) is seen by Belle recoiling against J/ψ in e^+e^- collisions. The state has a mass of 3943(11)(13) MeV and a width of 87(22)(26) MeV. The X is seen to decay to D D* and not to ωJ/ψ or D D. It is natural to attempt a 2P c ¯c assignment for this state since the expected mass of the 2^3P J multiplet is 3920 - 3980 MeV and the expected widths are 30 - 165 MeV. Finally, if the D D* mode is dominant it suggests that the X (3940) is the χ′ c. The problem with this assignment is that there is no evidence for the χ′ c in the same data. This has led Olsen to speculate that the X is the η″ c. Unfortunately this interpretation is also suspect because the η has an expected mass of 4064 MeV, 120 MeV too high.

2.8. Y (3940)

The Y (3940) is claimed as a resonance in the ωJ/ψ subsystem of the decay B → KπππJ/ψ with a mass of 3940(11) MeV and a width of 92(24) MeV. The state has not been seen in the decay modes Y → D D or D D*. Again, the mass and width of the Y suggest a radially excited P-wave charmonium. However, the ωJ/ψ decay mode is peculiar. In more detail, Belle measure Br(B → KJ)Br(Y → ωJ/ψ) = 5.0(9)(16) · 10^-5. One expects that Br(B → χ′ c) < Br(B → Kχ′ c) = 4(1) · 10^-4. This implies Br(Y → ωJ/ψ) > 12%, which is unusual for a canonical c ¯c state above open charm threshold.

Thus the Y is something of an enigma, driving the claim of the Belle collaboration that it is a hybrid. This is perhaps premature – certainly more data are required before strong claims can be made.

2.9. Z (3930)

This state was observed by the Belle collaboration in γγ → D D with a mass of 3931(4) MeV and a width of 20(8)(3) and a claimed significance of 5.5 sigma. The D D helicity distribution is consistent with J=2. In line with the X and the Y, the Z seems an obvious candidate for the χ" c (the χ' c cannot decay to D D). The predicted mass of the χ" c is 3972 MeV and the predicted width is 80 MeV. However, setting the mass to the measured 3931 MeV restricts phase space sufficiently that the predicted strong width drops to 47 MeV, reasonably close to the measurement. The predicted branching fraction to D D is 70%. The largest radiative transition is χ" c → ψ′ γ with a rate of 180(30) keV. At this stage we have no reason not to believe that the Z is the previously unknown χ" c.

2.10. Y (4260)

The Y (4260) was discovered as an enhancement in the ππJ/ψ subsystem of the reaction e^+e^- → γISRψππ with a mass of 4259(8)(4) MeV and a width of 88(23)(5) MeV by the BaBar collaboration. Evidently the state is a vector with c ¯c flavour.
Of course the low lying charmonium vectors are well known and the only mesonic charmonium vector available is the $\psi(3D)$. However quark model estimates of its mass place it at 4460 MeV, much too heavy for the $Y$. Of course this statement relies on the quark model itself – Llanes-Estrada has argued that the $Y$ is the $\psi(4S)$ based on the spectrum of a relativistic model. Maiani al. claim the $Y$ is a tetraquark $c\bar{c}s\bar{s}$ state which decays predominantly to $D_s\bar{D}_s$. Of the states which we know must exist, the most natural explanation is as a $c\bar{c}$ hybrid. The lightest charmonium hybrid is expected at 4400 MeV, somewhat high, but perhaps acceptable given our lack of experience in this sector.

Lastly, it is tempting to examine molecular interpretations of this state. In particular $D_D$ is an S-wave threshold at 4290 MeV – close enough that the enhancement may simply be a cusp effect. If the system does bind, it does so with a novel mechanism since pion exchange does not lead to a diagonal interaction in this channel (unlike the case of the $X(3872)$). Off-diagonal interactions may provide the required novelty.

3. Conclusions

The new heavy meson spectroscopy is no mere butterfly collecting – the $D_s$ spectrum and the $X$s, $Y$s, and $Z$s challenge our understanding of QCD. Can we rise to the challenge? It is clear that the simple constituent quark model must fail somewhere (gluonic degrees of freedom turn on, relativity and chirality become important, and coupled channels become dense) – are we seeing this? Lastly, have we entered a new era of ‘mesonic nuclear physics’?

Acknowledgments

This work was supported by PPARC grant PP/B500607 and the US Department of Energy under contract DE-FG02-00ER41135. I am grateful to Ted Barnes, Denis Bernard, Frank Close, Steve Godfrey, and Steve Olsen for many interesting discussions on the new states. I wish to thank the organisers and especially Xiangdong Ji for the invitation to discuss this fascinating topic in Beijing.

References

1. D. Acosta et al. [CDF Collaboration], arXiv:hep-ex/0505076.
2. I. F. Allison, C. T. H. Davies, A. Gray, A. S. Kronfeld, P. B. Mackenzie and J. N. Simone [HPQCD Collaboration], Phys. Rev. Lett. 94, 172001 (2005).
3. S. Godfrey and N. Isgur, Phys. Rev. D32, 189 (1985).
4. J. L. Rosner et al. [CLEO Collaboration], Phys. Rev. Lett. 95, 102003 (2005).
5. T. Barnes, S. Godfrey and E. S. Swanson, “Higher charmonia”, arXiv:hep-ph/0505002
   See also F. E. Close and E. S. Swanson, arXiv:hep-ph/0505206.
6. D.M. Asner et al. [CLEO], Phys. Rev. Lett. 92, 142001 (04).
7. C. Edwards et al. [CBALL], Phys. Rev. Lett. 48, 70 (82).
8. E. J. Eichten, K. Lane and C. Quigg, Phys. Rev. D 69, 094019 (2004).
9. E. S. Swanson, J. Phys. G 31, 845 (2005).
10. K. A. Abe et al. [Belle], hep-ex/0507033.
11. T. Barnes, F. E. Close and H. J. Lipkin, Phys. Rev. D 68, 054006 (2003).
12. A. V. Evdokimov et al. [SELEX Collaboration], Phys. Rev. Lett. 93, 242001 (2004).
13. K.-T. Chao, Phys. Lett. B599, 43 (04).
14. T. Barnes, F. E. Close, J. J. Dudek, S. Godfrey and E. S. Swanson, Phys. Lett. B 600, 223 (2004).
15. R. Kutschke, personal communication; E381-doc-701-v2.
16. B. Aubert et al. [BABAR Collaboration], arXiv:hep-ex/0408087.
17. R. Galik, talk presented at PIC2004.
18. S.-K. Choi et al. [Belle], Phys. Rev. Lett. 91 262001 (2003); V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 93, 162002 (2004); D. Acosta et al. [CDFII], Phys. Rev. Lett. 93, 072001 (04); B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 71, 071103 (2005).
19. L. Maiani et al., Phys. Rev. D71, 014028 (05).
20. D. Bugg, Phys. Lett. B598, 8 (04).
21. B.-A. Li, Phys. Lett. B605, 306 (05).
22. K. K. Seth, Phys. Lett. B 612, 1 (2005).
23. N. Tornqvist, hep-ph/0308277; F. E. Close and P. Page, Phys. Rev. B578, 119 (04).

For an overview see T. Barnes and S. Godfrey, Phys. Rev. D 69, 054008 (2004). For an effective field theory approach based on the weak coupling limit see E. Braaten and M. Kusunoki, Phys. Rev. D 72, 014012 (2005).
24. E. S. Swanson, Phys. Lett. B 588, 189 (2004); Phys. Lett. B 598, 197 (2004). For an example of light molecules see K. Dooley, E. S. Swanson and T. Barnes, Phys. Lett. B 275, 478 (1992).
25. K. Abe et al., arXiv:hep-ex/0505038.
26. K. Abe et al., arXiv:hep-ex/0505037.
27. K. Abe et al. [Belle Collaboration], arXiv:hep-ex/0408116.
28. CDF note 05-03-24.
29. BELLE-CONF-0540.
30. G. Bauer, arXiv:hep-ex/0505083; BELLE-CONF-0568; S. Olsen, private communication.
31. D. Bernard, talk at International Conference on QCD and Hadronic Physics, Beijing, June 2005.
32. K. Abe et al., arXiv:hep-ex/0507019.
33. But K. Trabelsi quotes a width of 39(26) MeV at Hadron05.
34. S. Olsen, private communication.
35. S.K. Choi et al. [Belle], Phys. Rev. Lett. 94, 182002 (05); K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 94, 182002 (2005).
36. B. Aubert et al. [BABAR Collaboration], arXiv:hep-ex/0506081.
37. F. J. Llanes-Estrada, Phys. Rev. D 72, 031503 (2005).
38. L. Maiani, V. Riquer, F. Piccinini and A. D. Polosa, Phys. Rev. D 72, 031502 (2005).
39. S. L. Zhu, Phys. Lett. B 625, 212 (2005); F. E. Close and P. R. Page, arXiv:hep-ph/0507199.