PROCEEDINGS OF SCIENCE

PoS(HEP2005)400

Hadronic Physics and Exotics

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I report on the state of hadronic physics and spectroscopy as reflected in contributions to the HEP2005 Europhysics Conference. Topics of interest include lattice field theory calculations of the hadron spectrum, the continuing quest to account for the proton's spin, pentaquarks, high-statistics Dalitz-plot analyses, excited charmed–strange mesons, quarkonium spectroscopy, and the new levels associated with the charmonium spectrum. I also reflect on the goals of hadronic physics and assess the current state of the art.

FERMILAB–CONF–05–356–T

International Europhysics Conference on High Energy Physics
July 21st - 27th 2005
Lisboa, Portugal

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[†]Fermilab is operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the U.S. Department of Energy.

1. Hadronic Physics Self-Assessment

Over the past three years, the discovery of many new states and remarkably incisive explorations of a broad range of phenomena have renewed interest in hadronic physics and spurred many lively conversations between theory and experiment. It seems appropriate, when the subject is in a healthy state of ferment, to begin with a brief assessment of the value and aspirations of hadronic physics.

Hadron phenomenology and spectroscopy does not test the standard model. We have a qualitative understanding of QCD phenomenology, but many aspects are not calculable from first principles. While we may learn how to refine our approximations to QCD, much analysis of experimental information relies on highly stylized, truncated pictures of the implications of the theory. We make models for new (and old!) states: approximations such as potential models, or intuitive pictures of substructure. The competing pictures are not mutually exclusive; quantum superpositions are possible. We will never discard QCD as the theory of the strong interactions if these pictures fail for the next state we find.

These are fair observations, and they merit our serious attention. I would note that there is value to both fundamental and applied science, and that the apparently less glamourous work of applied science may be just what we need to get at the fundamental lessons. Moreover, exploration—the task of discovering what phenomena exist and of developing systematics—helps us to understand what the fundamental questions are, and how we might best address them. It was, after all, the tension among the quark model of hadrons, the parton-model description of deeply inelastic scattering, and the nonobservation of free quarks that led us to quantum chromodynamics. The construction of a crossing-symmetric, Regge-behaved amplitude for linearly rising trajectories was a foundational event in string theory [1].

Physics doesn't advance by perturbation theory alone, and it is worth recalling that one of QCD's signal achievements is explaining what sets the mass of the proton—or, if you like, what accounts for nearly all the visible mass of the Universe. The insight that the mass of the proton arises from the energy stored up in confining three quarks in a small volume, not from the masses of the constituents themselves, is a landmark in our understanding of Nature [2]. The value of that insight isn't diminished because it is a little bit qualitative, or because a quantitative execution of the idea requires the heavy machinery of lattice field theory[1] [4, 5].

More generally, there is great value in a convincing physical picture that can show us the way to an answer (whether or not precise and controlled), or show that some tempting simplifying assumptions are unwarranted. The chiral quark model [6], which identifies the significant degrees of freedom on the 1-GeV scale as constituent quarks and Goldstone bosons, offers a nice example. It points to the *u*-*d* asymmetry in the light-quark sea of the proton [7], and predicts a negative polarization of the strange (but not antistrange) sea, casting doubt on a seemingly harmless assumption that underlies the Ellis–Jaffe sum rule [8]. A lifetime of staring at $\mathcal{L}_{\mathrm{QCD}}$ wouldn't lead to these expectations.

We can value *anschaulich* explanations as sources of intuition and instruments of exploration, while keeping clearly in mind their limitations, as we try to address many open-ended questions,

[1] See Ref. [3] for contributions to the Hadronic Physics parallel sessions.

including: What is a hadron? What are the apt degrees of freedom? What symmetries are fruitful? What are the implications of QCD under extreme conditions?

Emergent behavior—in the form of phenomena that are not simply derived from the underlying microphysics—is, moreover, quite ubiquitous in particle physics, and especially in hadronic physics. For example, as QCD becomes strongly coupled at low energies, new phenomena emerge that are not immediately obvious from the Lagrangian. Confinement and chiral symmetry breaking, with the implied appearance of Goldstone bosons, are specific illustrations. A graceful description entails new degrees of freedom that may be expressed in a model or—in the best of cases—in a new effective field theory.

The synthesis of principles through dialogue with experiment is central to the way hadronic physics is constructed, and runs through the agenda of the parallel sessions. I am firmly convinced that decoding hadronic phenomena in today's experiments develops habits of mind that we will cherish when the LHC brings surprises.

2. Where Does the Proton's Spin Reside?

Contributions to the parallel session reminded us that we do not have a complete answer to the question, "What is a proton?" The spin of a polarized proton may be partitioned among the quarks (and antiquarks), gluons, and orbital angular momentum according to the expression $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$. New measurements from the COMPASS experiment improve the determination of the quark-antiquark component to $\Delta\Sigma = 0.237^{+0.024}_{-0.029}$, and anchor the gluon contribution at $x = 0.1$ as $\frac{\Delta G}{G}(x_g = 0.1) = +0.024 \pm 0.089 \pm 0.057$ [9, 10]. At the same time, studies of transverse spin effects in the HERMES experiment give evidence for orbital angular momentum carried by the quarks [11]. BELLE also contributes to this program by measuring the fragmentation function of a transversely polarized quark [12]. This area offers but one example of diverse experiments making common cause.

3. Searching for Connections

The essence of doing science consists in *making connections* that lead us beyond independent explanations for distinct phenoma toward a coherent understanding of many phenomena. A network of understanding helps us see how different observations fit together and—very important—helps us know enough to recognize that something *doesn't fit.*

Connections among experiments or observations are not the only important ones. Whenever it is possible, we need to make connections between experimental systematics, phenomenological models, and the QCD Lagrangian—either directly, or through effective field theories, lattice field theory, or a controlled approximation to full QCD. I would also stress the potential value of reaching toward connections with our knowledge of nuclear forces and with the phenomena that occur in nuclear matter under unusal conditions.

We recognize different circumstances under which various approximations to QCD can be regarded as controlled expansions in small parameters. Nonrelativistic QCD applies to heavy-heavy $(Q_1\bar{Q}_2)$ mesons, for which the quark masses greatly exceed the QCD scale parameter, $m_{Q_i} \gg \Lambda_{\text{QCD}}$.

Befitting its aptness for the nonrelativistic limit, NRQCD takes as its expansion parameter v/c, the heavy-quark velocity divided by the speed of light. Heavy-quark effective theory (HQET) applies usefully to heavy-light ($Q\bar{q}$) systems, for which $m_Q \gg \Lambda_{\text{QCD}}$. In first approximation, the spin of the heavy quark is regarded as static, so the "light-quark spin" $\vec{j}_q = \vec{L} + \vec{s}_q$ is a good quantum number. The relevant expansion parameter is Λ_{QCD}/m_Q. Chiral symmetry is a valuable starting point for light quark systems ($q_1\bar{q}_2$) with $m_{q_i} \ll \Lambda_{\text{QCD}}$. In this case, the expansion parameter compares the current-quark mass to the scale of chiral-symmetry breaking, and is generally taken as $m_q/4\pi f_\pi$, where f_π is the pion decay constant. In a growing array of settings, lattice QCD embodies a controlled approximation that expresses the full dynamical content of the theory [13].

4. Seeking the Relevant Degrees of Freedom

Much of our insight into how hadrons behave follows from the simplifying assumption that mesons are quark–antiquark states, baryons are three-quark states, and that the quarks have only essential correlations. In the case of baryons, this reasoning leads us to the plausible starting point of SU(6) (flavor-spin) wave functions, which indeed offer a useful framework for discussing magnetic moments and other static properties. Some well-known observations, however, show us the limitations of the zeroth-order guess. If we examine deeply inelastic scattering in the limit as $x \to 1$, spin asymmetries indicate that the SU(6) wave functions are inadequate [14], and the ratio F_2^n/F_2^p is far from the uncorrelated expectation of $\frac{2}{3}$ [15].

Under what circumstances might it be fruitful—or even essential—to consider diquarks as physical objects [16]? The algebra of $\text{SU}(3)_c$ tells us that the $\mathbf{3}\otimes\mathbf{3}$ quark–quark combination is attractive in the $\mathbf{3}^*$ representation that corresponds to an antisymmetric diquark structure. A simple analysis suggests that the attraction of $[qq]_{\mathbf{3}^*}$ is half as strong as that of the $[q\bar{q}]_{\mathbf{1}}$ ($\mathbf{3}\otimes\mathbf{3}^* \to \mathbf{1}$) channel. For many years, it has seemed to make sense to regard members of the scalar nonet $\{f_0(600) = \sigma, \kappa(900), f_0(980), a_0(980)\}$ as $qq\overline{qq}$ states organized as $[[qq]_{\mathbf{3}^*}[\overline{qq}]_{\mathbf{3}}]_{\mathbf{1}}$ [17]. Recently, *intrinsic diquarks* ($|uuudc\bar{c}\rangle$) and intrinsic double-charm Fock states ($|uudc\bar{c}c\bar{c}\rangle$) have been advanced as an explanation of the production of the SELEX $\Xi(ccd)$ and $\Xi(ccu)$ states [18]. Diquarks as objects have elicited new attention under the stimulus of experimental evidence for pentaquark states [19, 20, 21]. (The attention to pentaquarks should be seen as part of a broader investigation into the existence of configurations, or body plans, beyond qqq and $q\bar{q}$.) That work, in turn, has led Wilczek and collaborators to revisit the Chew–Frautschi systematics of N,Δ resonances [22], and to assert that it is useful to view even low-spin, light baryons as $q[qq]_{\mathbf{3}^*}$ configurations. What can lattice QCD tell us about the shape of qqq baryons—both at the lowest spins and at high angular momenta [23]? Can the quark–diquark picture be reconciled with intuition from the $1/N_c$ expansion [24, 25]?

It is worth testing and extending the $q[qq]_{\mathbf{3}^*}$ proposal by considering its implications for doubly heavy (QQq) baryons. The comparison with heavy-light ($Q\bar{q}$) mesons offers a chance to calibrate the attractive forces in the $\mathbf{3}^*$ and color-singlet channels [26, 27]. Similarly, extending studies of the systematics of $qq\cdot\overline{qq}$ states to $Qq\cdot\overline{Q}\overline{q}$ states should, over the long term, develop and challenge the way we think about diquarks. Finally, in heavy-ion collisions, we should be alert for tests of the utility of diquarks in color–flavor locking, color superconductivity, and other novel phenomena.

Tugging the diquark concept this way and that will help elucidate the value of colorspin [28] as an organizing principle for hadron spectroscopy, and help us understand the relevance of color-nonsinglet spectroscopy [29]. Similar in their aspirations are the considerations of diquark–triquark configurations [30] and of the power of the chiral-soliton picture for baryon spectroscopy [31, 32, 33].

5. Exotic Baryons (Pentaquarks)

Over the past three years, numerous experiments have reported evidence for narrow exotic baryons carrying quantum numbers incompatible with the standard qqq body plan.[2] These reports include many sightings of $\Theta^+(\approx 1540)$, with K^+n quantum numbers; a recent claim of $\Theta^{++}(1530)$, with K^+p quantum numbers, in the STAR experiment at RHIC [35]; evidence for $\Xi^{--,0}(1862)$ and their antiparticles in the NA49 experiment at CERN; and evidence for a baryon with negative charm, $\Theta_c^0(3099)$, in the H1 experiment at DESY. All of these states could be interpreted as $qqqq\bar{q}$ pentaquarks, and those composed of light quarks u,d,s alone could be assigned to a $\mathbf{10}^*$ representation of flavor SU(3). It is by no means obvious on dynamical grounds that narrow pentaquarks should populate full multiplets. Quantitative information about pentaquarks—or other states that lie beyond the 1960s quark model,[3] but within the spectrum allowed by quantum chromodynamics—would allow us to refine heuristic pictures of hadron structure and sharpen our understanding of QCD in the confinement limit. Accordingly, the pentaquark candidates have elicited much theoretical attention.

Many sensitive, high-resolution experiments do not support the observation of pentaquarks. Indeed, *no claim is unchallenged*, and it is hard to argue that every experiment—whether offering positive or negative evidence—is both significant and correctly interpreted.

Recently, the two experiments that began the pentaquark rush have reported new data. The LEPS experiment [37] has taken new runs on liquid hydrogen and liquid deuterium targets. In the reaction $\gamma d \to K^- pX$, they see excesses in the mass spectrum of particles recoiling against K^-p at 1.53 GeV and 1.6 GeV; at the lower peak, the ratio of signal to $\sqrt{\text{signal}+\text{background}}$ is approximately 5. The CLAS experiment at JLab has taken data on hydrogen and deuterium with samples about an order of larger than in their original experiment. In $\gamma p \to K_S K^+ n$ with approximately 1500 counts per 4-MeV bin, they see no Θ^+ signal [38]. There is also no sign of Θ^+ in their $\gamma d \to K^- pK^+ n$ sample [34]; an increased estimate of background reduces the significance of their original claim to $\approx 3\sigma$.

Here in Lisbon, we have heard limits on pentaquark production in Z^0 decays from the DELPHI experiment [39]; the nonobservation of Θ^+, Ξ^{--} in the HERA-B experiment [40]; and status reports on the contending evidence on strange and charmed pentaquarks from the $e^{\pm}p$ collider experiments H1 and ZEUS [41, 42]. The B-factory experiments BaBar and Belle reported limits on pentaquark production based on the study of interactions with detector elements [43, 44], a lovely technique.

The case for exotic baryons remains unproved. If you wonder how it could be possible for an apparently robust signal, confirmed in multiple experiments, to prove misleading, I refer you to the great sensation of the 1969 Lund Conference, the two-peak structure of the split-A_2 (now a_2) meson [45].

[2] See Volker Burkert's summary at Uppsala [34] for a recent survey of the evidence.
[3] Exotic $qq\bar{q}\bar{q}$ "tetraquarks," for example [36].

6. Dalitz-Plot Analyses

Among many parallel-session contributions on production and decay dynamics, I would like to point to three applications of Dalitz-plot techniques that are representative of a new era in the extraction of decay amplitudes and relative phases. CLEO-*c* reports a large number of studies in progress [46]. Among them, the aim of determining the strong phase between the decays $D^0 \to K^\pm K^{*\mp}$ for extraction of $\phi_3 = \gamma$ from $B^\pm \to K^\pm K^{*\mp} K^\pm$ has a direct practical application.

In BaBar's study of the $D^0 \to \bar{K}^0 K^+ K^-$ Dalitz plot, the dominant channels are seen to be $D^0 \to \bar{K}^0 a_0(980), \bar{K}^0 \varphi, K^- a_0^+(980)$ [47]. The amplitude information offers new possibilities for studying the scalar nonet, which is also a target of the KLOE studies of $e^+e^- \to \varphi \to \gamma f_0(980), \gamma a_0(980)$ [48]. KLOE has also examined 5-γ and 7-γ final states in the reaction $e^+e^- \to \varphi \to \gamma\eta$. Their noteworthy results include a measurement of the slope parameter in the $\pi^0\pi^0\pi^0$ channel and a determination of the branching fraction $\mathcal{B}(\eta \to \pi^0\gamma\gamma) = (8.4 \pm 2.7 \pm 1.4) \times 10^{-5}$, about ten times smaller than a 1984 GAMS result, and in line with chiral perturbation theory

7. Beyond Idealizations

There is potentially great value to be gained by stretching our models and calculations beyond the domains in which we first encountered them. By leaving the comfort zone, we may happen on effects that were unimportant—or concealed—in the original setting. An excellent example is the prospect of extending our descriptions of the ψ $(c\bar{c})$ and Υ $(b\bar{b})$ systems to the spectrum of B_c $(b\bar{c})$ mesons [49]. Several factors contribute to the theoretical interest in B_c. The $b\bar{c}$ system interpolates between heavy-heavy $(Q\bar{Q})$ and heavy-light $(Q\bar{q})$ systems. The unequal-mass kinematics and the fact that the charmed quark is more relativistic in a $b\bar{c}$ bound state than in the corresponding $c\bar{c}$ level imply an enhanced sensitivity to effects beyond nonrelativistic quantum mechanics.

The new element in $b\bar{c}$ theory is lattice QCD calculations that include dynamical quarks. A Glasgow–Fermilab collaboration predicts $M(B_c) = 6304 \pm 20$ MeV [50]. Establishing the B_c ground state in nonleptonic decays—$\pi J/\psi, a_1 J/\psi$ are the most promising final states—will pin down the mass with greater certainty than is possible in the semileptonic $J/\psi\ell\nu$ channel. A first measurement by the CDF experiment in the $J/\psi\pi$ channel gives $M(B_c) = 6287 \pm 5$ MeV [51], in pleasing agreement with the lattice computation. Beginning to reconstruct some part of the $b\bar{c}$ spectrum in γ or $\pi^+\pi^-$ cascades to the ground state will be an experimental *tour-de-force.*

Let us take a moment to review some elementary points about meson taxonomy that are relevant to intermediate cases—including the $b\bar{c}$ system. Two useful classification schemes are familiar in atomic spectroscopy as the *LS* and jj coupling schemes. Any state can be described in any scheme, through appropriate configuration mixing, but it is prudent to keep in mind that a choice of basis can guide—or maybe misguide—our thinking.

For equal-mass meson systems ($q\bar{q}$ or $Q\bar{Q}$) it is traditional to couple the orbital angular momentum, $\vec{L}$, with the total spin of the quark and antiquark, $\vec{S} = \vec{s}_q + \vec{s}_{\bar{q}}$. This is the standard practice for light mesons, and is now familiar for the designation of quarkonium ($c\bar{c}$ and $b\bar{b}$) levels. The good

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quantum numbers are then S, L, and J, with $\vec{J} = \vec{L} + \vec{S}$, and we denote the spin-singlet and spin-triplet levels as ${}^1\mathrm{S}_0 - {}^3\mathrm{S}_1$; ${}^1\mathrm{P}_1 - {}^3\mathrm{P}_{0,1,2}$; ${}^1\mathrm{D}_2 - {}^3\mathrm{D}_{1,2,3}$; and, in general, as ${}^1L_L - {}^3L_{L-1,L,L+1}$.

In the case of heavy-light ($Q\bar{q}$) mesons, it is suggestive to couple the difficult-to-flip heavy-quark spin, $\vec{s}_Q$, with the "light spin," $\vec{j}_q = \vec{L} + \vec{s}_q$. The good quantum numbers are then L, j_q, and J, where $\vec{J} = \vec{s}_Q + \vec{j}_q$, and the low-lying levels are

$$L = 0: \quad j_q = \tfrac{1}{2}: \quad 0^- \text{ - } 1^-$$
$$L = 1: \; j_q = \begin{cases} \tfrac{1}{2}: & 0^+ \text{ - } 1^+ \\ \tfrac{3}{2}: & 1^+ \text{ - } 2^+ \end{cases} \quad \text{, etc.}$$

In the absence of configuration mixing, this classification implies that the $j_q = \frac{3}{2}$ states will decay only through the d-wave, and so will be narrow. The $j_q = \frac{1}{2}$ states, for which s-wave decay is allowed, will in general be broad. It bears emphasis that the D_s, B_s systems could be exceptions to this rule, because of the limited phase space available for kaon emission.

It makes sense to seek out intermediate cases wherever we can find them. We expect, for example, mixed 1^+ levels in the $B_c = b\bar{c}$ spectrum, but detailed information is not likely to be in our hands soon. A more accessible case might be that of the strange particles ($s\bar{q}$), for which the $q\bar{q}$-inspired LS classification has been the standard. Perhaps some unexpected insights might come from considering strange mesons as heavy-light ($Q\bar{q}$) states [52]. In any event, it is worth asking how infallible is the intuition we derive from regarding D_s states as heavy-light.

Here in Lisbon, we heard an indication from the Belle experiment that configuration mixing may not be negligible for the 1^+ D_s levels. An angular analysis of the decay $D_{s1}(2536) \to D^{*+}K_S$ indicates the presence of a large s-wave amplitude [53]. That is to say, the putative $j_\ell = \frac{3}{2}$ state seems not to decay in a pure d-wave. Nevertheless, $D_{s1}(2536)$ remains narrow, with a total width less than 2.3 MeV. Is this because the $j_\ell = \frac{1}{2}$ level with which it might mix is anomalously narrow (as we shall recall next), or is there another explanation for the small s-wave width?

Two states that might be identified as the $j_q = \frac{1}{2}$ $c\bar{s}$ levels are well established, the 0^+ $D^*_{sJ}(2317) \to D_s\pi^0$ and 1^+ $D_{sJ}(2460) \to D_s\gamma, D^*_s\pi^0$. Their centroid lies some 135 MeV below that of the $j_\ell = \frac{3}{2}$ states, the 1^+ $D_{s1}(2536)$ and 2^+ $D^*_{s2}(2573)$. The low masses disagree with relativistic potential model predictions, and mean that the expected strong decay by kaon emission is kinematically forbidden.

The fact that $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$ appeared in isospin-violating decays stimulated interpretations beyond the standard $c\bar{s}$ body plan, including DK molecules and tetraquarks. It is noteworthy that the BaBar experiment looked for, but did not find, partners with charge 0 or ± 2 [54]. Radiative decay rates should be an incisive diagnostic [55]. For any interpretation of the D_{sJ} states, it is imperative to predict what happens in the B_s system. Experimenters need not wait for the theorists to place their bets. Tracking down the B_{sJ} analogues should be a high priority for CDF and DØ!

I think the evidence is persuasive that the D_{sJ} levels are ordinary $c\bar{s}$ states at lower masses than anticipated, and I find it intriguing that these states might give us a window on chiral symmetry in a novel setting [56, 57, 58]. Let us suppose that, contrary to standard intuition in light-quark systems, chiral symmetry and confinement might coexist in heavy–light mesons. Then we would expect to observe chiral supermultiplets: states with orbital angular momenta $L, L+1$, but the same value of j_q.

Specifically, we should find the paired doublets

$$j_q = \tfrac{1}{2} : 1\mathrm{S}(0^-, 1^-) \text{ and } 1\mathrm{P}(0^+, 1^+);$$
$$j_q = \tfrac{3}{2} : 1\mathrm{P}(1^+, 2^+) \text{ and } 1\mathrm{D}(1^-, 2^-).$$

Chiral symmetry predicts equal hyperfine splitting in the paired doublets, $M_{D_s(1^+)} - M_{D_s(0^+)} = M_{D_s(1^-)} - M_{D_s(0^-)}$, in agreement with what is observed. So far, the predictions for decay rates match experiment [59, 60]. In addition to confronting chiral symmetry's predictions for the D_s and other families, we need to ask to what extent the coexistence of chiral symmetry and confinement is realized in QCD, and how chiral symmetry may be restored in excited states [61].

8. Quarkonium Spectroscopy

In the parallel sessions, we had the pleasure of hearing a flood of beautiful new results on ψ and Υ spectroscopy. Here are some of the highlights.

The CLEO experiment reported the discovery of the long-sought $h_c(1^1\mathrm{P}_1)$level in $\psi' \to \pi^0 h_c$ [62]. The mass of the new state, $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV, is about 1 MeV below the $1^3\mathrm{P}_J$ centroid. Belle reported extensive studies of $\gamma\gamma \to \eta_c, \chi_{c0}, \chi_{c2} \to h^+h^-, h^+h^-h^+h^-$ [63]. Several of the rates $\Gamma(\eta_c \to \gamma\gamma)\mathcal{B}(\eta_c \to f)$ are about one-third of current world averages [64]. CLEO has observed the rare decay $\psi(3770) \to \pi\pi J/\psi$ at a branching fraction $\mathcal{B}(\psi(3770) \to \pi^+\pi^- J/\psi) = (214 \pm 25 \pm 22) \times 10^{-5}$ [65]. This is important engineering information for anticipating the properties of the $1^{1,3}\mathrm{D}_2$ levels. They have identified a rare radiative decay of ψ'', with a partial width $\Gamma(\psi(3770) \to \gamma\chi_{c1}) = 75 \pm 18$ keV [66]. Finally—in the charmonium sector—the KEDR experiment in Novosibirsk has employed resonance depolarization techniques to make precise energy determinations that enable them to characterize the masses $M(\psi') = 3686.117 \pm 0.012 \pm 0.015$ MeV and $M(\psi'') = 3773.5 \pm 0.9 \pm 0.6$ MeV [67].

In the $b\bar{b}$ sector, CLEO has presented another measurement of great engineering significance, the determination of the $B_s^{(*)}$ yield on the 5S resonance: $\mathcal{B}(\Upsilon(5S) \to B_s^{(*)}\bar{B}_s^{(*)}) = 16.0 \pm 2.6 \pm 6.3\%$ [68], and has made a precise determination of the 1S, 2S, and 3S leptonic widths [69]. One number that shows the quality of the measurements is $\Gamma(\Upsilon(1\mathrm{S}) \to e^+e^-) = 1.336 \pm 0.009 \pm 0.019$ keV. Such information will provide a good test of lattice calculations of the bottomonium spectrum [70] and provides needed input for improved potential-model descriptions. There is also news about hadronic cascades. The Belle experiment has observed 38 ± 6.9 events consistent with the transition $\Upsilon(4\mathrm{S}) \to \pi^+\pi^-\Upsilon(1\mathrm{S})$, corresponding to a branching fraction $\mathcal{B} = (1.1 \pm 0.2 \pm 0.4) \times 10^{-4}$ [63]. CLEO has offered evidence for the first observation of hadronic cascades not involving a $^3\mathrm{S}_1$ level, determining partial widths $\Gamma \approx 0.9$ keV for the transitions $\chi_b'(2^3\mathrm{P}_{2,1}) \to \pi^+\pi^-\chi_b(1^3\mathrm{P}_{2,1})$ [69].

9. New States Associated with Charmonium

In the three years since the Belle Collaboration announced the observation of the $2^1\mathrm{S}_0$ $c\bar{c}$ state in exclusive B decays [71], new states have arrived in great profusion. In addition to the $1^1\mathrm{P}_1$ $h_c(3524)$

level already mentioned [72], we have credible evidence for five new particles connected with the charm-anticharm system. The best known of these is $X(3872)$ [73], clearly established in several experiments. On current evidence, it is likely to be a $J^{PC} = 1^{++}$ state, and is *probably not charmonium*. More about the $X(3872)$ shortly.

The remaining particles need confirmation; each has been seen only in a single experiment so far. Belle [73] has reported $Y(3940 \pm 11)$ in the decay $B \to K\omega J/\psi$; it is a relatively broad state, with a total width $\Gamma = 92 \pm 24$ MeV. Belle also reports the state $X(3936 \pm 14)$, seen in $e^+e^- \to J/\psi + X$ [74]. It is observed to decay into $D\bar{D}^*$, but not $D\bar{D}$, which suggests an unnatural parity assignment. The total width is $\Gamma = 39 \pm 24$ MeV. These characteristics make $X(3936)$ a plausible $\eta_c''(3^1\mathrm{S}_0)$ candidate [75, 76].

Belle has observed a narrow ($\Gamma \approx 20$ MeV) state in $\gamma\gamma \to D\bar{D}$ that they call $Z(3931 \pm 4 \pm 2)$ [77]. The production and decay characteristics are consistent with a 2^{++} assignment, and this state is a plausible χ_{c2}' $(2^3\mathrm{P}_2)$ candidate [75, 76]. The most recent addition to the collection is $Y(4260)$, a 1^{--} level seen by BaBar in $e^+e^- \to \gamma\pi^+\pi^- J/\psi$ [78], with supporting evidence from $B \to K^- J/\psi\pi\pi$ [79].

As if seven new states were not enough, there are more charmonium levels to be found [80, 81]. Two of these—the unnatural parity $1^{1,3}\mathrm{D}_2$ states that should lie between $D\bar{D}$ and $D\bar{D}^*$ threshold—have been anticipated for three decades. The 2^{--} $\psi_2(3831)$ $(1^3\mathrm{D}_2)$ state should be seen to decay into $\gamma\chi_{c1,2}$ and $\pi\pi J/\psi$, but not to $D\bar{D}$. Its hyperfine partner, the 2^{-+} $\eta_{c2}(3838)$ $(1^1\mathrm{D}_2)$, should be observed in decays to γh_c and $\pi\pi\eta_c$, but not to $D\bar{D}$. Then there are a couple of states, along with the $2^3\mathrm{P}_2$ and perhaps $3^1\mathrm{S}_0$ levels mentioned above, that we have only come to anticipate as narrow on the basis of recent coupled-channel calculations. These are the 3^{--} $\psi_3(3868)$ $(1^3\mathrm{D}_3)$, which should be observed as a quite narrow ($\Gamma \lesssim 1$ MeV) peak in $D\bar{D}$, and the 4^{++} $\psi_4(4054)$ $(1^3\mathrm{F}_4)$, which should also be seen as a $D\bar{D}$ resonance with $\Gamma \lesssim 5$ MeV. And let us not forget the possibility that gluonic degrees of freedom will manifest themselves in the form of hybrid $c\bar{c}g$ levels [82, 83, 84].

All of these Xs and Ys are very confusing, so we may have to admit that our alphabet is not rich enough to accommodate the new reality of charmonium spectroscopy. By good fortune, Dr. Seuss, author of the children's classic, *O Gato do Chapéu*, has anticipated our need and extended the latin alphabet to include new letters such as quan, yekk, spazz, and floob [85]. Should we assign to the Particle Data Group the responsibility of deciding which particle is a yekk and which a floob, or should that honor rest with the discoverers?

10. What is $X(3872) \to \pi\pi J/\psi$?

The $X(3872)$ is the best studied of the new $c\bar{c}$-associated states, and it has been subjected to a broad range of diagnostic tests. Upon discovery, $X(3872)$ seemed a likely candidate for ψ_2 (or perhaps ψ_3), but the expected radiative transitions to χ_c states have never been seen. The $\pi\pi$ mass spectrum favors high dipion masses, suggesting a $J/\psi\,\rho$ decay that is incompatible with the identification of $X(3872) \to \pi^+\pi^- J/\psi$ as the strong decay of a pure isoscalar state. Observing—or limiting—the $\pi^0\pi^0 J/\psi$ decay remains an important goal. An observed $J/\psi\,3\pi$ decay suggests an appreciable transition rate to $J/\psi\,\omega$. Belle's 4.4-σ observation of the decay $X(3872) \to J/\psi\,\gamma$ determines $C = +$, opposite to the charge-conjugation of the leading charmonium candidates. Finally, an analysis of angular distributions supports the assignment $J^{PC} = 1^{++}$, but the mass of $X(3872)$ is too low to be gracefully identified with the $2^1\mathrm{P}_1$ charmonium state, especially if $Z(3931)$ is identified as the $2^3\mathrm{P}_2$ level. [It is important to note that our expectations for charmonium states above $D\bar{D}$ threshold have matured to include the coupling of $c\bar{c}$ levels with open charm.]

If $X(3872)$ is not a charmonium level, what might it be? Three interpretations take the near-coincidence of the new state's mass and the $D^0\bar{D}^{*0}$ to be a decisive clue: an s-wave cusp at $D^0\bar{D}^{*0}$ threshold [86], a $D^0 - \bar{D}^{*0}$ "molecule" bound by pion exchange [87, 88, 89, 90], and a diquark–antidiquark "tetraquark" state $[cq][\overline{cq}]$ [91, 92, 93]. What distinctive predictions might allow us to put these interpretations to the test? On the threshold enhancement interpretation, we should expect bumps at many thresholds, but no radial or orbital excitations. If pion exchange is decisive, then there should be no analogue molecule at $D_s\bar{D}_s^*$ threshold. The tetraquark interpretation suggests that $X(3872)$ should be split into two levels, because $[cu][\overline{cu}]$ and $[cd][\overline{cd}]$ would be displaced by about 7 MeV. If diquarks are useful dynamical objects, there should be a sequence of excited states as well.

The implication that $X(3872)$ could be resolved into two states has already attracted experimental attention from BaBar [79]. The evidence is far from decisive, but I report it to you as an illustration of the lively dialogue between experiment and theory that has characterized this subject. 61.2 ± 15.3 events that fit the hypothesis $B^- \to K^- X(3872)$ lead to a mass of $3871.3 \pm 0.6 \pm 0.1$ MeV, whereas 8.3 ± 4.5 $B^0 \to K^0 X(3872)$ events yield $3868.6 \pm 1.2 \pm 0.2$ MeV. The mass difference, $2.7 \pm 1.3 \pm 0.2$ MeV, doesn't yet distinguish between one X and two. The same study compares the ratio of the charged and neutral decays, $\mathcal{R} \equiv \mathcal{B}(B^0 \to K^0 X(3872))/\mathcal{B}(B^- \to K^- X(3872)) = 0.50 \pm 0.30 \pm 0.05$, to be compared with the expectations of the tetraquark ($\mathcal{R} \approx 1$) and molecule ($\mathcal{R} \lesssim 0.1$) pictures.

Braaten & Kusunoki [94] have called attention to a fascinating phenomenon (known in nuclear physics as a Feshbach resonance) that should occur if a dynamical level and a threshold coincide: an extremely large scattering length that is governed (inversely) by the difference between the bound-state energy and the threshold. I do not think that $X(3872)$ meets the conditions, but we should be attentive for this circumstance—perhaps even for one of the other new states.

The campaign to understand $X(3872)$ has called on numerous heuristic pictures, and has spurred theorists to elaborate simple images into calculational tools. Coupled-channel potential models appear to be useful interpretive tools; they have help us learn what $X(3872)$ is not, and we will see how helpful they can be in making sense of the other new states. One can only be impressed with the increasing effectiveness of lattice QCD (below threshold) [13, 95, 70]. We still await a definitive sighting of the influence of the gluonic degrees of freedom on the spectrum of quarkonium or states related to quarkonium. To test our understanding of $X(3872)$ and the other new states, it would be extremely helpful to know what happens in the $b\bar{b}$ system. For a more extensive recent discussion of the new states in the charmonium system, see Ref. [96].

11. Outlook[4]

Hadronic physics is rich in opportunities. Models—disciplined by principles—are wonderful exploratory tools that can help us to uncover regularities and surprises. It is important that phenomeno-

[4]See Ref. [97] for a different emphasis and more expansive view of the subject.

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logical studies make contact at every opportunity with symmetries and with lattice QCD, especially as the incorporation of dynamical quarks becomes routine. Our goal—it is the goal of all science—must be to build coherent networks of understanding, not one-off interpretations of data. In both experiment and theory, in both exploration and explanation, we profit by tuning between systems with similar but not identical characteristics, and by driving models beyond their comfort zones.

In spectroscopy, I see much to be gained from a comparison of the hadronic body plans we know: quark–antiquark mesons and three-quark baryons, with the diversity that springs from light and heavy quarks. Light-quark mesons, heavy-light mesons, and heavy quarkonia call upon different elements of our theoretical armamentarium, as do baryons containing 3, 2, 1, or 0 light quarks—but all are hadrons, and some of what we learn in one setting should serve us in another. Do other body plans occur in Nature—two-quark–two-antiquark mesons, four-quark–one-antiquark baryons, and more? What rôle do diquarks play in determining the hadron spectrum and interactions? And what lessons might we draw from the behavior of hadronic matter under unusual conditions, including those that prevail in heavy-ion collisions?

High-rate experiments more incisive than ever before are giving us new looks at familiar phenomena and new opportunities to exploit established techniques. Dalitz-plot analyses offer exquisite sensitivity to small amplitudes and access to phase information. We are gaining a richer understanding of diffraction, hadronization, and the structure of the proton.

In addition to the specific measurements I have mentioned and that others have highlighted in the course of this meeting, I would like to underscore the value of broad searches for new mesons and baryons. BaBar's discovery of D_{sJ} and Belle's string of observations remind us that you don't have to know precisely what you are looking for to find something interesting: combining a convenient trigger particle with an identifiable hadron or two—$(J/\psi \text{ or } \Upsilon) + \pi, \pi\pi, K, K_S, p, \Lambda, \gamma, \eta, \omega, \ldots$—can be very profitable indeed.

In experiment and theory alike, let us use our models and our truncated versions of QCD to guide our explorations and organize our understanding. Let us keep in mind the limitations of our tools as we focus on what we can learn of lasting value. Let us, above all, try to discern where the real secrets are hidden.

Acknowledgments

I am grateful to Pepe Bernabéu and the Organizing Committee for their kind invitation to present this report, and for the stimulating and enjoyable atmosphere of HEPP2005. I thank Helen Quinn for her thought-provoking comments on hadronic physics, delivered at *Heavy Quarks and Leptons 2004*. Andreas Kronfeld called my attention to Ref. [85]. Jon Rosner offered helpful advice.

It is my pleasure to thank Karin Daum and Gerhard Mallot for their insightful work as convenors of the Hadronic Physics parallel sessions, and to acknowledge the important contributions of the forty-three speakers. I regret that I could not discuss every contribution in this short summary.

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