Theoretical Overview: The New Mesons

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Abstract. After commenting on the state of contemporary hadronic physics and spectroscopy, I highlight four areas where the action is: searching for the relevant degrees of freedom, mesons with beauty and charm, chiral symmetry and the D_{sJ} levels, and $X(3872)$ and the lost tribes of charmonium.

1. Introduction

1.1. Three Cheers for QCD!

It has been a good season for Quantum Chromodynamics. Just a few days ago, the Royal Swedish Academy of Sciences awarded the 2004 Nobel Prize in Physics to David Gross, David Politzer, and Frank Wilczek, "for the discovery of asymptotic freedom in the theory of the strong interaction." I hope that all of you have not only taken pleasure in the recognition accorded to our friends and their work [1, 2], but also have taken some time to reflect on the developments that preceded and followed from the discovery of asymptotic freedom,[1] and to share your understanding of the remarkable edifice that is QCD with your colleagues at home.

The discovery of asymptotic freedom and the understanding of what it could mean marked a tipping point in the long struggle to make sense of the strong interactions, but it could only have appeared in a rich context. If by chance you have never read the seminal papers, or if it has been a long time since you enjoyed them, let me point you to a short selection of the classics. The idea of a vector gluon theory may be found in a prescient paper by Nambu [3], and the case for a color gauge theory is made by Gell-Mann and collaborators [4, 5, 6]. Perceiving the broad reach of the antiscreening property of non-Abelian gauge theories required an understanding of the Callan [7] – Symanzik [8] renormalization group equations, which many physicists of a certain age acquired from Sidney Coleman's Erice lecture notes [9]. And, of course, the tension that asymptotic freedom relieved was created by the successes of the quark model, the unavailing searches for free quarks, the experimental observation [10] of Bjorken scaling [11], and the intuitive appeal of the parton model [12, 13]. Now is the perfect time to refresh your appreciation of this wonderful saga, and to look ahead to what else we might make.

1.2. Spectroscopy Is Alive and Well

The occasion to celebrate past glories isn't the only reason to see this as a good season for QCD. The talks we have just heard by Gabriella Sciolla [14] and Steve Olsen [15] are emblematic of

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[1] A good starting place is the informal history to be found at `http://nobelprize.org/physics/laureates/2004/phyadv04.pdf`.

a most remarkable renaissance in hadron spectroscopy now in full bloom. Over the past few years, experiments have uncovered a plethora of new narrow states that extend our knowledge of hadrons and challenge our understanding of the strong interaction.

In the heavy-flavor arena that I shall emphasize, first came the discovery in the Belle experiment of η_c' in exclusive $B \to KK_SK^-\pi^+$ decays [16]. CLEO [17], BaBar [18], and Belle [19] have confirmed and refined the discovery of η_c' in $\gamma\gamma$ collisions, fixing its mass and width as $M(\eta_c') = 3637.7 \pm 4.4$ MeV and $\Gamma(\eta_c') = 19 \pm 10$ MeV [20]. The unexpectedly narrow D_{sJ} states discovered by Babar [21], CLEO [22], and Belle [23] provided the next surprise. Then followed the discovery by Belle [24] of $X(3872) \to \pi^+\pi^-J/\psi$, rapidly confirmed by CDF [25], DØ [26], and BaBar [27]. This year, it appears that we may finally have solid evidence for h_c, the 1^1P_1 level of charmonium, from E835 [28] and CLEO [29, 30]. We have just heard [15] that Belle has sighted one or more interesting peaks in the neighborhood of 3940 MeV. On the baryon side, SELEX has reported signals for a family of doubly charmed baryons, beginning with $\Xi_{cc}^+(3519)$ [31]. And the broad $j_q = \frac{1}{2}$ charm levels are coming under increasing experimental scrutiny [32, 33, 34, 35].

In the light-quark sector, evidence has been accumulating for exotic $J^{PC} = 1^{-+}$ mesons [36, 37] that do not correspond to $q\bar{q}$ states. Conflicting evidence on pentaquarks, baryon states with quantum numbers that do not occur in the simple qqq quark-model description of baryons, continues to provoke lively discussion [38, 39, 40, 41].

Each of the new states raises questions of interpretation, and offers opportunities to challenge—and deepen—our understanding. The conversation between theory and experiment, and among different experiments, has been lively and stimulating.

1.3. The Value of Hadronic Physics

It is good to engage in lively conversations; it is even better to reach significant conclusions about the way Nature works. And there the exploratory—and, not infrequently, wooly—character of hadronic physics means that the path to fundamental lessons may be indistinct. The hadronic physics community needs to think about how it spends its time—and why.

In her opening lecture at *Heavy Quarks and Leptons 2004*, Helen Quinn [42] made the following observations to explain her emphasis on the weak interactions:

> 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. We make models for new states: approximations such as potential models, or intuitive pictures of substructure. The competing pictures are not mutually exclusive; quantum superpositions are possible. We'll never throw out QCD if these pictures turn out not to work for the next state we find. We do learn how to refine our approximations to QCD.

These are fair and thoughtful observations. How do you respond?

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.

At the same time, a little self-awareness (even self-criticism) can make for better science. We need to distinguish between exploratory models and controlled approximations, to pay attention to whether we are testing theories or theorists (both activities have some social value), and to ask whether we are probing close to the Lagrangian of Quantum Chromodynamics or comparing random numbers with experiment.

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 [43]. 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.

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 [44], 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 [45], and predicts a negative polarization of the strange (but not antistrange) sea. A lifetime of staring at $\mathcal{L}_{\text{QCD}}$ 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, 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?

1.4. The Theory of Everything

There is another reason to contemplate the style of analysis that characterizes hadronic physics and its relationship to fundamental insights. In a provocative article, Laughlin & Pines [46] trumpet the end of reductionism ("the science of the past," which they identify with particle physics) and the triumph of emergent behavior, the study of complex adaptive systems ("the physics of the next century"). By *emergent,* we understand phenomena that are not simply derived from the underlying microphysics—a Lagrangian, say—but are governed by "higher organizing principles" (perhaps universal), relatively independent of the fundamental theory. If these clever fellows were better listeners, I believe they would come to understand that even the top-down string theorists they view as arch-reductionists are, in truth, paragons of the emergent impulse. What could be more emergent than the conviction that our standard model will arise out of the multiple vacua of M theory and the string-theory landscape?

Emergence is, moreover, quite ubiquitous in particle physics, and especially in the hadronic physics we are discussing at this meeting. 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 other hallmark of the kind of science that Pines and Laughlin advocate is the synthesis of principles through experiment. This too is central to the way hadronic physics is constructed, and runs through the agenda of this workshop. So I think that these earnest scholars are promoting a combat that need not exist. For my part, I can't imagine creating physics without both reduction and synthesis, and I think it would be foolish to follow only one approach.[2]

I hope you will take time, during this meeting and beyond, to reflect on the roles of microscopic parameters and emergent phenomena in hadronic physics and in your own work. The topics on the agenda lend themselves to building a bridge between the spareness of the Lagrangian and the richness of emergent behavior; they can benefit from a range of approaches, and they should stimulate rewarding conversations among physicists with different sensibilities.

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[2] It might be interesting to muse on whether seeing a given set of phenomena as emergent represents a transient stage in our evolving understanding or a final state. Such considerations call for a highly cerebral bottle of wine.

1.5. Making Connections; Controlling Approximations

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 our 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.

My colleague Estia Eichten [47] likes to emphasize the 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, $m_{Q_i} \gg \Lambda_{QCD}$. 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 $m_Q \gg \Lambda_{QCD}$. 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 $m_{q_i} \ll \Lambda_{QCD}$. 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.

2. Searching for the Relevant Degrees of Freedom

Much of our insight into the comportment of hadrons 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 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 [48], and the ratio[3] F_2^n/F_2^p is far from the uncorrelated expectation of $\frac{2}{3}$.

Under what circumstances might it be fruitful—or even essential—to consider diquarks as physical objects [50]? The algebra of 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 $qq\bar{q}\bar{q}$ states organized as $[[qq]_{\mathbf{3}^*}[\bar{q}\bar{q}]_{\mathbf{3}}]_{\mathbf{1}}$ [51]. 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 [52]. Diquarks as objects have elicited new attention under the stimulus of experimental evidence for pentaquark states [53, 54, 55]. (The attention to pentaquarks should be seen as part of a broader investigation into the existence of configurations 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 [56], 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 [57]? Can the quark–diquark picture be reconciled

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[3] For a clear exposition of issues related to the neutron-proton ratio, see Ref. [49].

with intuition from the $1/N_c$ expansion [58, 59]?

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. Similarly, extending studies of the systematics of $qq \cdot \bar{q}\bar{q}$ states to $Qq \cdot \bar{Q}\bar{q}$ 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 [60] as an organizing principle for hadron spectroscopy.

3. Mesons with Beauty and Charm

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 [61]. Establishing the B_c ground state in nonleptonic decays—$\pi J/\psi, a_1 J/\psi$ are the most promising final states—to pin down the mass with greater certainty than is possible in the semileptonic $J/\psi\ell\nu$ channel and beginning to reconstruct some part of the spectrum in γ or $\pi^+\pi^-$ cascades to the ground state will be an experimental *tour-de-force.*

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. At this meeting, Andreas Kronfeld reports new predictions [62, 63] for the mass of the $b\bar{c}$ ground state on behalf of a Glasgow–Fermilab subset of the High-Precision QCD Collaboration.[4] Using quarkonium as a baseline, they quote a preliminary value, $M_{B_c} = 6304 \pm 3 \pm 3 \pm 11^{+0}_{-12}$ MeV; using a heavy-light baseline, they find $M_{B_c} = 6253 \pm 17 \pm 3 \pm 11^{+30-50}_{-0}$ MeV. They are making final studies of the sensitivity to lattice spacing and the sea-quark mass, and expect to present a final result soon.

4. Chiral Symmetry and the D_{sJ} Levels

In early 2003, the Babar [21], CLEO [22], and Belle [23] experiments presented convincing evidence for two new narrow charmed-strange mesons, $D_s(2317) \to D_s\pi^0$ and $D_s(2459) \to D_s^*\pi^0$. These states, which are candidates for the $j_q = \frac{1}{2}$ $c\bar{s}$ levels with $J^{PC} = 0^{++}$ and 1^{++}, are curious on several counts. Their centroid is well below that of the corresponding $j_q = \frac{3}{2}$ states $D_{s1}(2535)$ and $D_{s2}^*(2572)$, in disagreement with relativistic quark model predictions [66].[5] And although we anticipated that the $j_q = \frac{1}{2}$ D_s and B_s states might be narrower than their nonstrange counterparts, because of the limited phase space for kaon emission [68], these states are seen in isospin-violating decays; the standard decay channels are kinematically forbidden. The unexpected properties of these states have provoked much discussion [69, 70, 71, 72], including speculations that they might be multiquark or molecular states.

Before looking into interpretations of the narrow charmed-strange states, let us take a moment to review some elementary points about meson taxonomy. 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.

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[4] See also the talks by Alan Gray on bottomonium [64] and by Jim Simone on charmonium [65].

[5] See Alexey Drutskoy's talk [67] for an update on Belle's observations.

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 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 $^1S_0 - {}^3S_1$; $^1P_1 - {}^3P_{0,1,2}$; $^1D_2 - {}^3D_{1,2,3}$; 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

$$L = 0: \quad j_q = \tfrac{1}{2}: \qquad 0^- \text{ - } 1^-$$

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

$$\text{etc.}$$

In the absence of configuration mixing, this classification implies that the $j_q = \tfrac{3}{2}$ states will decay only through the d-wave, and so will be narrow. The $j_q = \tfrac{1}{2}$ states, for which s-wave decay is allowed, will in general be broad.

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 that 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 [73]. In any event, it is worth asking how infallible is the intuition we derive from regarding D_s states as heavy-light.

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 [74]. 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

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

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

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, and so far, the predictions for decay rates match experiment.[6] 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.

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!

5. The Lost Tribes of Charmonium

One of the liveliest areas of heavy-flavor spectroscopy has been the renewed exploration of charmonium and the discovery of several new states [75]. Two sets of states have been missing for a long time from our experimental inventory: $c\bar{c}$ states below $D\bar{D}$ threshold, and unnatural-parity $c\bar{c}$ states that lie between $D\bar{D}$ and $D\bar{D}^*$ thresholds [76]. In the first category, we count

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[6] For more details, see Estia Eichten's talk [72].

the 1^1P_1 h_c, a $J^{PC} = 1^{+-}$ expected to lie close to the ^3P_J centroid at 3525.3 MeV, and the 2^1S_0 η_c', the $J^{PC} = 0^{-+}$ hyperfine partner of $\psi'(3686)$. The η_c' is now firmly established, and good evidence for the h_c is mounting [28, 29, 30]. The second category includes the η_{c2}, the 1^1D_2 $J^{PC} = 2^{-+}$ level, and its hyperfine partner, the $J^{PC} = 2^{--}$ 1^3D_2 state, ψ_2. The discovery of $X(3872)$ is the first evidence for a narrow state in the interthreshold region. We do not yet know whether it is, in fact, a charmonium state.

The motivation for a continuing examination of the charmonium spectrum—even before the additional surprises we have heard from Steve Olsen [15]—is that there are many states to study, we know there is more to QCD than potential models embody, and we hope to find experimental evidence for that additional richness. New experimental tools offer another stimulus: the opportunity to access J^{PC} quantum numbers that were, until recently, difficult to reach. The discovery of $X(3872)$ has prompted the realization that there may be additional narrow $c\bar{c}$ states with allowed, but inhibited, decays to open charm, and that these might constitute the beginning of a new facet of charmonium spectroscopy [77, 78, 79]. The most promising cases are 1^3D_3, 2^3P_2, and 1^3F_4.

At first sight, it seems natural to think of $X(3872)$ as the missing $^3D_2$ level of charmonium, but some pieces of evidence do not fit gracefully with that hypothesis. The mass is higher than the 3815 MeV expected in a single-channel potential model, and the radiative decays $X(3872) \to \gamma\chi_{c1,2}$—expected to be prominent, or even dominant—have not been detected. Other charmonium states have been explored [80, 77, 78], but the $^3D_3$ level that seems to me most promising still requires the discovery of a strong radiative transition to χ_{c2}. It is important to remark that our expectations for radiative branching fractions depend on knowing the decay rate for $X(3872) \to \pi^+\pi^- J/\psi$. The theory of hadronic cascades is primitive, and the normalizing rate, $\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi)$ is poorly known. The absence of signals for $\gamma\gamma \to X$ [81, 82] argues against some off-beat charmonium interpretations. Evidence for a large ($\approx 84\%$) prompt X signal at the Tevatron [83, 84] and the similarity of $X(3872)$ production characteristics to those of ψ' in 2-TeV proton–antiproton collisions [26] are in accord with the charmonium hypothesis.

The coincidence of $X(3872)$ with the $D^0\bar{D}^{*0}$ threshold at 3871.5 MeV also invites alternative interpretations, including an s-wave $D\bar{D}^*$ threshold cusp in the 1^{++} channel [85, 86], and deuteron-like "molecules" formed by pion exchange between D^0 and $\bar{D}^{*0}$ [87, 88, 89, 90, 91]. In the favored 1^{++} channel, the hadronic cascade must be $X(3872) \to (\pi^+\pi^-)_{I=1}J/\psi$. If the observed dipion cascade is the tail of ρ^0, and if Belle's $\pi^+\pi^-\pi^0 J/\psi$ [15] represents the tail of $\omega J/\psi$, those features would fit nicely with the molecular interpretation. Characterizing the dipion through a study of angular distributions [92] is an urgent matter for experiment.

Hybrid ($c\bar{c}g$) states might exist, and these have been put forward as candidates for $X(3872)$ [93, 94, 95]. However, lattice calculations predict that the lightest charmonium hybrids should lie in the neighborhood of 4.3 GeV($J^{PC} = 1^{-+}$), 4.7 GeV(0^{+-}), and 4.9 GeV(2^{+-}) [96], and BaBar has seen no evidence for an enhanced $X \to \eta J/\psi$ decay rate [97].

None of these interpretations implies a charged partner for $X(3872)$, and none has been seen [98].

While we have much work to do to pin down the nature of $X(3872)$,[7] I want to emphasize that *there are more states to be found.* Belle has given us a hint of a narrow state at 3940 MeV decaying into $D\bar{D}^*$ [15, 99]. Perhaps it is the 2^3P_2 charmonium level, perhaps the coincidence with the $D_s\bar{D}_s$ threshold at 3936.2 MeV is more than coincidence? And then there is Belle's broader (?) $\omega J/\psi$ bump near the same mass. If you stare long enough at the $\pi^+\pi^- J/\psi$ discovery spectra for $X(3872)$, you may see another, less prominent, peak about 40 MeV below. Is it there? What limits can we set on other $\pi^+\pi^- J/\psi$ states?

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[7] Long lists of experimental and theoretical tasks can be found in my BEACH04 lecture [75].

The discovery of the narrow state $X(3872) \to \pi^+\pi^- J/\psi$ gives charmonium physics a rich and lively puzzle. We do not yet know what this state is. If the most conventional interpretation as a charmonium state—most plausibly, the 1^3D_2 or 1^3D_3 level—is confirmed, we will learn important lessons about the influence of open-charm states on $c\bar{c}$ levels. Should the charmonium interpretation not prevail, perhaps $X(3872)$ will herald an entirely new spectroscopy. In either event, several new charmonium states remain to be discovered through their radiative decays or hadronic transitions to lower $c\bar{c}$ levels. Another set of $c\bar{c}$ states promises to be observable as narrow structures that decay into pairs of charmed mesons. In time, comparing what we learn from this new exploration of the charmonium spectrum with analogous states in the $b\bar{b}$ and $b\bar{c}$ families will be rewarding. For all three quarkonium families, we need to improve our understanding of hadronic cascades. Beyond spectroscopy, we look forward to new insights about the production of quarkonium states in B decays and hard scattering. The rapid back-and-forth between theory and experiment is great fun, and I look forward to learning many new lessons!

6. Concluding Observations

Hadron spectroscopy 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 phenomenological 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.

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? And what lessons might we draw from the behavior of hadronic matter under unusual conditions, including those that prevail in heavy-ion collisions?

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 closing, I'd like to return to Helen Quinn's friendly challenge and urge you to take those observations to heart in the way you carry out your research and in the way you present it to others. 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.

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