Theoretical summary of the conference

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The Constituent Quark Model has provided a remarkable description of the experimentally observed hadron spectrum but still has no firm theoretical basis. Attempts to provide a QCD justification discussed at Hadron99 include QCD Sum Rules, instantons, relativistic potential models and the lattice. Phenomenological analyses to clarify outstanding problems like the nature of the scalar and pseudoscalar mesons and the low branching ratio for $\psi' \to \rho - \pi$ were presented. New experimental puzzles include the observation of $\bar{p}p \to \phi\pi$.

1. INTRODUCTION

Is there a theory?

QCD is supposed to explain everything about Hadron Spectroscopy - But How?

QED is supposed to explain everything about Superconductivity - But How?

Will explaining Hadron Spectroscopy from first principles using QCD be as difficult as explaining Superconductivity from first principles using QED?

1.1. The Sakharov-Zeldovich 1966 quark model (SZ66)

Andrei Sakharov, a pioneer in quark-hadron physics asked in 1966 "Why are the Λ and Σ masses different? They are made of the same quarks". Sakharov and Zeldovich[1]. assumed a quark model for hadrons with a flavor dependent linear mass term and hyperfine

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interaction,

$$M = \sum_i m_i + \sum_{i>j} \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i \cdot m_j} \cdot v_{ij}^{hyp} \tag{1}$$

where m_i is the effective mass of quark i, $\vec{\sigma}_i$ is a quark spin operator and v_{ij}^{hyp} is a hyperfine interaction with different strengths but the same flavor dependence for qq and $\bar{q}q$ interactions.

This model can be considered analogous to the BCS description of superconductivity. The constituent quarks are quasiparticles of unknown structure with a background of a condensate. They have effective masses not simply related to the bare current quark masses, and somehow including all effects of confinement and other flavor independent potentials. The only contribution to hadron masses not already included is a flavor-dependent two-body hyperfine interaction inversely proportional to the product of these same effective quark masses. Hadron magnetic moments are described simply by adding the contributions of the moments of these constituent quarks with Dirac magnetic moments having a scale determined by the same effective masses. The model describes low-lying excitations of a complex system with remarkable success.

1.2. Striking results and predictive power

Sakarov and Zeldovich already in 1966 obtained two relations between meson and baryon masses in remarkable agreement with experiment. Both the mass difference $m_s - m_u$ between strange and nonstrange quarks and their mass ratio m_s/m_u have the same values when calculated from baryon masses and meson masses[1]

$$\langle m_s - m_u \rangle_{Bar} = M_\Lambda - M_N = 177\,\mathrm{MeV} \tag{2}$$

$$\langle m_s - m_u \rangle_{mes} = \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi}{4} = 180\,\mathrm{MeV} \tag{3}$$

$$\left(\frac{m_s}{m_u}\right)_{Bar} = \frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} = 1.53 = \left(\frac{m_s}{m_u}\right)_{Mes} = \frac{M_\rho - M_\pi}{M_{K^*} - M_K} = 1.61 \tag{4}$$

Further extension of this approach led to two more relations for $m_s - m_u$ when calculated from baryon masses and meson masses[2,3]. and to three magnetic moment predictions with no free parameters[4,5]

$$\langle m_s - m_u \rangle_{mes} = \frac{3M_\rho + M_\pi}{8} \cdot \left(\frac{M_\rho - M_\pi}{M_{K^*} - M_K} - 1\right) = 178\,\mathrm{MeV}. \tag{5}$$

$$\langle m_s - m_u \rangle_{Bar} = \frac{M_N + M_\Delta}{6} \cdot \left(\frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} - 1\right) = 190\,\mathrm{MeV}. \tag{6}$$

$$\mu_\Lambda = -0.61\,\mathrm{n.m.} = \mu_\Lambda = -\frac{\mu_p}{3} \cdot \frac{m_u}{m_s} = -\frac{\mu_p}{3} \frac{M_{\Sigma^*} - M_\Sigma}{M_\Delta - M_N} = -0.61\,\mathrm{n.m.} \tag{7}$$

$$-1.46 = \frac{\mu_p}{\mu_n} = -\frac{3}{2} \tag{8}$$

$$\mu_p + \mu_n = 0.88\,\mathrm{n.m.} = \frac{M_p}{3m_u} = \frac{2M_p}{M_N + M_\Delta} = 0.865\,\mathrm{n.m.} \tag{9}$$

Also in 1966 Levin and Frankfurt[6] noted a remarkable systematics in hadron-nucleon total cross sections indicating that mesons and baryons were made of the same basic building blocks. The analysis supporting their ratio of 3/2 between baryon-nucleon and meson-nucleon cross sections has been refined[7] and consistently confirmed by new experiments[8]. Most recently the new SELEX measurement[9] $\sigma_{tot}(\Sigma p) = 36.96 \pm 0.65$ at P = 609 GeV/c agrees with the prediction $\sigma_{tot}(\Sigma p) = 37.07$ mb. from the 1975 two-component-Pomeron model (TCP)[10], which also fit all σ_{tot}, data now fit by PDG[11] with fewer free parameters. QCD calculations have not yet explained such remarkably successful simple constituent quark model results. A search for new experimental input to guide us is therefore of interest.

1.3. How to go beyond SZ66 with QCD

Many approaches are being investigated to use QCD in the description of hadron spectroscopy. Some of these discussed at Hadron99 include: The lattice, bag models, QCD Sum Rules[12,13], Instantons[14], Phenomenology[15–17], Relativistic Potential Models[14] and Reggeism and the Pomeron. Unfortunately there has been no significant confirmation of any of these approaches by the kind of agreement with experiment and the predictive power seen in the constituent quark model. The complexity of QCD calculations necessitates the introduction of ad hoc approximations and free parameters to obtain results, thus losing the simplicity of the constituent quark model, with its ability to make many independent predictions with very few parameters, There is also a tendency to lose some of the good results of the constituent quark model; namely

- The universal treatment of mesons and baryons made of the same quarks
- The spin dependence of hadron masses as a hyperfine interaction
- The appearance of the same effective quark masses in hadron masses, spin splittings and magnetic moments
- The systematic regularities relating meson-nucleon and baryon-nucleon cross sections

While none of these results can be considered to have a firm theoretical foundation based on QCD, it is difficult simply to dismiss the striking agreement with experiment and the successful predictive power as purely accidental.

The lattice approach, which seems to have a firm foundation in QCD, has concentrated in attempting to fit known properties of hadrons rather than predicting new hadron physics. In the one area awaiting new exciting physics, the possible existence of glueballs, there are ambiguous predictions and still no clear data. Hopefully these ambiguities will be clarified by the next Hadron Spectroscopy conference.

Underlying all the puzzles and paradoxes in hadron spectroscopy is the nature of the pion, which seems to be at the same time a Goldstone boson and 2/3 of a proton and a member of a pseudoscalar nonet whose masses are closer to the proton mass than to the pion mass.

Present attempts to describe hadrons recall the story of the blind men and the elephant[18] . Each investigation finds one particular property of hadrons and many contradictory conclusions arise,; e.g (1) A pion is a Goldstone Boson and a proton is a Skyrmion, (2) a pion is two-thirds of a proton. The simple quark model prediction $\sigma_{tot}(\pi^- p) \approx (2/3) \cdot \sigma_{tot}(pp)$ [6,7] still fits experimental data better than 7% up to 310 GeV /c[8]; (3) Mesons and Baryons are made of the same quarks. Describing both as simple composites of asymptotically free quasiparticles with a unique effective mass value predicts hadron masses, magnetic moments and hyperfine splittings[1–3]. (4) Lattice QCD can give all the answers, (5) Lattice calculations disagree on whether the H dibaryon is bound and offer no hope of settling this question until much bigger lattices are available[18]. (5) Light (uds) SU(3) symmetry and Heavy Quark symmetry (cbt) are good; (6) Light (uds) SU(3) symmetry is bad. All nontrivial hadron states violate SU(3). All light V, A and T mesons have good isospin symmetry with flavor mixing in (u.d) space and no $s\bar{s}$ component; e.g. ρ, ω. (7) The s-quark is a heavy quark. Flavor mixing in mass eigenstates predicted by SU(3) is not there. Most nontrivial strange hadron states satisfy (scb) heavy quark symmetry with no flavor mixing.; e.g. ϕ, ψ, Υ.

1.4. Glueballs and hybrids

The question of whether there are any hadron states which contain constituent gluons remains open. The main frontier here is experimental[19], with searches for possible candidates described in detail at Hadron99. A theoretical review of the status of glueballs and hybrids has been given by Narison[12]

2. SCALAR AND PSEUDOSCALAR MESONS

The lowest nine vector mesons are simply described as an ideal U(3) nonet with states constructed from all possible combinations of (u,d,s) quark-antiquark pairs. and with U(3) broken only by the difference between the masses of the strange and nonstrange quarks. The lowest-lying pseudoscalar and scalar states are very different and still present a confused picture in the hadron spectrum.

Most theoretical treatments treat scalars and pseudoscalars very differently, with the pseudoscalar mixing arising from a peculiarly pseudoscalar mechanism like PCAC, the low mass of the pion, and the U(1) problem. In contrast Metsch[14] treats both scalars and psudoscalars on the same footing and attributes the deviation from the ideal vector spectrum to a single interaction due to instantons. Whether this can provide a complete answer remains to be seen.

New experimental input that can resolve many of the controversial issues can be expected from investigations of heavy-quark hadron decays into final states including these mesons[20,21].

2.1. Problems with the σ, a_0 and f_0

The scalar meson spectrum begins with three lowest lying states which do not easily fit into any nonet: the σ, whose existence is still in question and the a_0 and f_0. The general tendency here is to introduce other configurations than $q\bar{q}$ for these states[13].

The question of whether the a_0 and f_0 mesons are $q\bar{q}$ states, $K\bar{K}$ molecules or four-quark states is still open and controversial. All points of view were expressed at Hadron99.

Narison[12] using QCD spectral sum rules suggests that the a_0 is a $q\bar{q}$ state, while the f_0 is a quarkonium-gluonium mixture. Achasov[15] presents considerable phenomenological evidence for the four-quark nature of the a_0 and f_0. Metsch[14] describes the f_0 in the instanton model as a $q\bar{q}$ state in the lowest scalar nonet but has no place for the a_0. Maltman[13] uses QCD Finite Energy Sum Rules to calculate the decay constants rather than the spectrum and suggests that scalar decay constants probe a spatial extent.

Although no data on charmed meson decays into these controversial pseudoscalars were presented at Hadron99, data presenting clear and extremely interesting evidence for the existence and properties of the σ as a light scalar $\pi^+\pi^-$ resonance observed in $D^+ \rightarrow \pi^+\pi^-\pi^+$ decay[20] and for the masses and widths of f_0 observed in $D_s^+ \rightarrow \pi^+\pi^-\pi^+$ decay[21] has been obtained at Fermilab. The data should be available very soon, before the publication of these proceedings.

2.2. Problems with the η and η'

The pseudoscalars are conventionally described by adding an additional mass contribution to the SU(3) singlet state, thus breaking U(3) while conserving SU(3) and leaving SU(3) breaking as entirely due to quark mass differences. The physical mesons η and η' are then described as mixtures described by a mixing angle either of the SU(3) singlet and octet states or of the strange and nonstrange states analogous to the physical ω and ϕ vector mesons. Both mixing angles have been used at this conference[12,14]. The dynamical origin of this additional singlet contribution is still unclear and controversial, with some models attributing it the annihilation of an $q\bar{q}$ pair into gluons or instantons[14] and the creation of a $q\bar{q}$ pair of a different flavor. Since the annihilation and creation processes are short-range and the amplitudes are proportional to the initial and final state wave functions at the origin there is no reason to limit the mixing to only ground state $q\bar{q}$ wave functions and admixtures of radial excitations[22,14] and glueballs have been considered.

3. THE INTERFACE BETWEEN HEAVY FLAVOR PHYSICS AND HADRON SPECTROSCOPY

3.1. Exotic multiquark hadrons - a window into QCD

Two striking features of the hadron spectrum are (1) the absence of strongly bound multiquark exotic states like a dipion with a mass less than two pion masses or a dibaryon bound by 100 MeV. and (2) the description of nuclear constituents as three-quark clusters called nucleons with no explicit quark degrees of freedom. The constituent quark model gives a very simple explanation[23]. The one gluon exchange ansatz for $V(q\bar{q})_8/V(q\bar{q})_1$ and $V(qq)_6/V(qq)_{3*}$ gives:

- Color-exchange color-electric interaction saturates[24] - no forces between color singlet hadrons.
- Color electric energy unchanged by color recoupling.
- Color magnetic qq forces repulsive for a single flavor - attractive between s quark in D_s or B_s and u and d quarks in proton.
- Energy gain by color-spin recoupling can bind H (hexaquark)[26], charmed and beauty pentaquarks[18,31–36] $P_c = \bar{c}suud$; $P_b = \bar{b}suud$.

The validity of this simple picture still remains to be confirmed by experiment since no experimental information is yet available about short-range color-sextet or color-octet two-body interactions. All constituent quark model successes with a two-body color-exchange interaction[2–4,24] and all hadron spectroscopy without exotics including scattering depend only upon $(\bar{q}q)_1$ and $(qq)_{3*}$ interactions.

Since physically realizable beams contain at least one u or d quark or antiquark, hadron-nucleon scattering in the (u,d,s) sector is dominated either by resonances produced by $\bar{q}q$ annihilation or by the repulsive color-magnetic interaction keeping apart two hadrons containing quarks of the same flavor. Only with more than three flavors can the $(qq)_6$ or $(\bar{q}q)_8$ interactions be observed in realistic scattering experiments with no common flavor between beam and target. Thus the possible existence of exotic hadrons remains crucial to understanding how QCD makes hadrons from quarks and gluons[25].

The H dibaryon[26] was shown to have a gain in color-magnetic energy over the $\Lambda\Lambda$ system[26,27]. But a lattice calculation[28] showed a repulsive Λ-Λ interaction generated by quark exchange[29,30] not included in simple model calculations which could well prevent the six quarks from coming close enough together to feel the additional binding of the short range color-magnetic interaction. Pentaquarks, shown [31–36] to have a color-magnetic binding roughly equal to the H, have no possible quark exchange force in the lowest decay channel D_sN [29]. The simplest lattice calculation can easily be done in parallel with the more complicated H calculation both in the symmetry limit where all light quarks have the same mass and with $SU(3)$ symmetry breaking. Comparing results may provide considerable insight into the physics of QCD in multiquark systems even if the pentaquark is not bound. However, no such lattice calculation has been done or is planned.

The experimental searches for the H abd the pentaquark have been summarized [37,38] with so far no conclusive evidence for either. A few candidate pentaquark events have been reported[39,40], but the evidence that these are not due to systematic errors is not convincing. A better approach would be to search with a good vertex detector and good particle ID for secondary vertices where one of the particles emitted from the secondary vertex is unambiguously a proton[18]. This immediately identifies the particle as a weakly decaying baryon and something new and interesting if its mass is not equal to the mass of the known charmed or beauty baryons.

3.2. New $b\bar{c}$ spectroscopy and possible tetraquarks

The new $b\bar{c}$ mesons found at Fermilab introduce a new field of hadron spectroscopy. In addition to the normal meson spectrum, there is the question of bcq baryons and $bc\bar{u}\bar{d}$ tetraquarks. The bc diquark can be produced in a high energy hadron experiment with cross sections comparable to the $b\bar{c}$ meson. The bc diquark can then capture a light quark q to produce a bcq baryon. But the bc diquark will have a much smaller size than diquarks containing lighter flavors and can appear on the light quark mass scale as a point particle with the color quantum numbers of an antiquark. The bc diquark can therefore attract two light antiquarks to produce a $bc\bar{u}\bar{d}$ tetraquark with a light quark wave function similar to that of an antibaryon containing one heavy antiquark.

3.3. Interface between QCD and weak decays

Are there pseudoscalar or scalar resonances near the D and D_s masses; e.g. the $\pi(1800)$? If so, how do they affect weak decays. There is room for both theoretical and experimental investigation. Many final state channels are open in this mass range and similarities in branching ratios for strong and weak decays can provide interesting clues to the structure of these hadrons. In particular, there could be evidence for hybrid structure[41].

The B and D decays to η, η', σ, f_0 and a_0 can provide new and independent information regarding the structure of these controversial mesons. The decay $B \to K\eta'$ is much too large for any model, while $B \to K\eta$ is much smaller and not yet seen. However in the final states with a K^* rather than a K, the decay $B \to K^*\eta$ has been seen and $B \to K^*\eta'$ has not. The decay $D_s \to f_0\pi$ is strongly seen in the decays $D_s \to 3\pi$[21]. Will $D_s \to a_0\pi$ be seen in $D_s \to \eta\pi$? The $D \to \sigma\pi$ has been seen in $D \to 3\pi$[20].

While the search for new evidence of CP violation provides the main motivation for investigations of B and D decays, the interpretation of these decays requires some input from final state interactions and QCD. Thus there is another connection between heavy flavor physics and hadron spectroscopy.

3.4. Is the strange quark a heavy quark?

Most nontrivial strange hadron states satisfy (scb) heavy quark symmetry with no flavor mixing.; e.g. ϕ, ψ, Υ. The strange axial mesons are particularly interesting. The triplet and singlet quark spin states $^3P_1$ and $^1P_1$ which are SU(3) eigenstates are badly mixed. HQET couples the light quark spin to the orbital $L = 1$ to get to doublets with j=1/2 and j=3/2 instead of a triplet and a singlet. Which is it?

4. OPEN PUZZLES IN HADRON SPECTROSCOPY

4.1. Constituent quarks vs. current quarks

Hadron spectroscopy tends to describe the known mesons and baryons as $q\bar{q}$ and $3q$ systems. However, deep inelastic scattering experiments lead to a description of hadrons containing these states as valence quarks and adding a sea of quark-antiquark pairs and gluons[42]. There seems to be a general consensus that this picture should not be discussed in detail in a Hadron Spectroscopy conference. It is interesting hadron physics, but belongs elsewhere; e.g. in meetings on the spin structure of the nucleon, strangeness in the nucleon and deep inelastic scattering. However, a few points from this picture did arise at the conference.

4.1.1. The observation of $\bar{p}n \to \phi\pi$; strangeness in the proton?

Does this observation[16] indicate strangeness in the nucleon or perhaps something more exciting?

If $\bar{p}n \to \phi\pi$, then $\phi\pi \to \bar{p}n$. This would be the first experimental evidence for structure in $\phi\pi$ scattering in one partial wave. What are the dynamics of this scattering? Does it go via a hybrid or some other exotic state that couples to $\phi\pi$? What other final states are coupled to this partial wave in $\phi\pi$ scattering? More clever experiments are needed to unravel this mystery.

4.1.2. The spin structure of the Λ

In the constituent quark model the Λ contains two nonstrange quarks whose spins are coupled to spin zero and the strange quark carries the entire spin of the baryon. But in the picture where strange quarks carry some of the spin of the proton, the nonstrange quarks carry some of the spin of the Λ. Possible experimental tests of this description were discussed[42].

4.2. The $\psi' \to \rho\pi$ dilemma

That the experimental ratio of the branching ratios $BR(\psi' \to \rho\pi)/BR(J\psi \to \rho\pi)$ is much smaller than the experimental values for ratios of decays of ψ' and $J\psi$ into other decay modes is well known and so far defies all theoretical explanations. An update of this problem was resented[17].

4.3. Heavy flavor decays to pseudoscalar mesons

The ratios of the D_s branching ratios $BR(D_s \to \eta'\pi)/BR(D_s \to \eta\pi)$ and $BR(D_s \to \eta'\rho)/BR(D_s \to \eta\rho)$ are both much too large to be explained by any conventional model.

5. CONCLUSIONS

There are many theoretical approaches to applying QCD to hadron spectroscopy. No one seems far superior to the others. There are strong disagreements between various approaches to the description of the scalar and pseudoscalar mesons. New data can help resolve these open questions.

Some open puzzles:
$\bar{p}p \to \phi\pi$ and $\phi\pi \to ??$
$\psi' \to \rho\pi$

Interface with heavy flavor physics should be developed; e.g. D and B decays to f_0, a_0, η and η'.

Exotic tetraquarks ($bc\bar{u}\bar{d}$) and pentaquarks ($\bar{Q}suud$) should be investigated both experimentally and theoretically.

Possible applications of HQET also considering the strange quark as a heavy quark

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