ISSUES IN LIGHT MESON SPECTROSCOPY: THE CASE FOR MESON SPECTROSCOPY AT CEBAF

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ABSTRACT

I review some outstanding issues in meson spectroscopy. The most important qualitative issue is whether hadrons with explicit gluonic degrees of freedom exist. To answer this question requires a much better understanding of conventional $q\bar{q}$ mesons. I therefore begin by examining the status of conventional meson spectroscopy and how the situation can be improved. The expected properties of gluonic excitations are discussed with particular emphasis on hybrids to give guidance to experimental searches. Multiquark systems are commented upon as they are likely to be important in the mass region under study and will have to be understood better. In the final section I discuss the opportunities that CEBAF can offer for the study of meson spectroscopy.

1. Introduction

It is twenty years since the birth of Quantum Chromodynamics [1], the theory of the strong interactions, and it is not yet clear what the physical states of the theory are. This is an extraordinary statement that we still cannot answer such a basic and fundamental question. Although there is growing evidence for the existence of hadrons with no valence quark content or with an excited glue degree of freedom, we still do not really know if such states exist. An analogy in QED might be not knowing whether positronium existed or not. Clearly we cannot say that we understand QCD until these questions are answered. We have a powerful tool to better understand QCD through the the interplay of theory and experiment. A better understanding of QCD, a non-Abelian gauge theory, will also lead to a better understanding of other non-Abelian gauge theories such as the standard model of the electroweak interaction.

Since it is possible that it may be further decades before we have a thorough theoretical understanding of QCD in the low $Q^2$ confinement region, we must rely heavily on the insights we can gain from experiment and QCD based models. To a large extent our understanding of hadron structure is based on the constituent quark model in which mesons are made of a quark and antiquark and baryons are made of three quarks [2,3]. However, an important consequence of QCD is the expectation that
exotic hadrons beyond the naive quark model should also exist; *hybrids*, *glueballs*, and $q\bar{q}q\bar{q}$ states. Perhaps the discovery of such *exotica* will help us understand *Soft QCD*. The problem is that although there are several exotic meson candidates, no exotic has been unambiguously identified. What has happened to them? Answering this question has become the major preoccupation of hadron spectroscopists. In this contribution I review the expected properties of *conventional* and *exotic* mesons and how these states might be studied at CEBAF.

As an operational definition I will refer to states predicted by the constituent quark model as *conventional* hadrons and those lying outside the quark model as *exotic* hadrons. I emphasize, however, that there is nothing fundamental about the quark model and the physical states of the theory should be based on the gauge invariant operators one can construct in QCD and will in general include gluonic excitations [4]. Nevertheless, states predicted by the quark model are the only ones that have been unambiguously identified. Finding new types of hadronic matter — the *hybrids* which have constituent quarks and an excited glue degree of freedom and *glueballs* which have no valence quark content what-so-ever [5] is the most important qualitative question in hadron spectroscopy. A serious impediment to the discovery of such states is the sad shape of hadron spectroscopy. In particular, none of the light meson spectra is well mapped out for either orbital or radial excitations. There are also numerous puzzles in light meson spectroscopy, for example, the scalar meson puzzle, the nature of the $f_1(1420)$ and the $f_0(1720)$, and the $g_T$ mesons. The first priority is to sort out light meson spectroscopy so that we have a template against which to compare exotic candidates.

Despite the shape of conventional meson spectroscopy it is the discovery of gluonic excitations in the hadron spectrum which is the most important issue in hadron spectroscopy as it will signify a qualitative difference with the quark model. The primary purpose of the next generation of hadron experiments should be to discover glueballs, hybrids, and other exotic hadrons. There are numerous models describing such states with important qualitative differences so that the discovery of exotics is important to distinguish between the different models and make progress in understanding *soft QCD*.

2. Conventional Mesons

The Quark Model is 30 years old! It is a useful tool for understanding hadron spectroscopy but we still don’t understand why it works. To make progress we need to fill in some of the missing states so that we can either verify the model, find out where it needs to be refined, or possibly show it is wrong. In our quest for *exotic* hadrons we should not forget that *conventional* $q\bar{q}$ mesons can also tell us much about the nature of confinement. For example, the linear Regge trajectories of orbitally excited mesons is a consequence of the linear confining potential [6] and the splittings of orbitally excited multiplets reflects the Lorentz structure of the confining potential [7]. The better we understand hadrons, the more we can test the quark model and ultimately, better understand QCD.
Table 1. The quantum numbers of the conventional $q\bar{q}$ mesons.

| $L$ | $S$ | $J^{PC}$ | $I=1$ | $I=0$ $(n\bar{n})$ | $I=0$ $ss$ | Strange |
|-----|-----|----------|-------|------------------|--------------|---------|
| 0   | 0   | 0--     | $\pi$ | $\eta$ | $\eta'$ | $K$ |
| 1   | 0   | 1--     | $\rho$ | $\omega$ | $\phi$ | $K^*$ |
| 1   | 1   | 1++     | $b_1$ | $h$ | $h'$ | $K_1$ |
| 1   | 0   | 0++     | $a_0$ | $f_0$ | $f_0'$ | $K_0^*$ |
| 1   | 1   | 1++     | $a_1$ | $f_1$ | $f_1'$ | $K_1$ |
| 1   | 2   | 2++     | $a_s$ | $f_2$ | $f_2'$ | $K_2^*$ |
| 2   | 0   | 2--     | $\pi_2$ | $\eta_2$ | $\eta_2'$ | $K_2$ |
| 2   | 1   | 1--     | $\rho_1$ | $\omega_1$ | $\phi_1$ | $K_1^*$ |
| 2   | 2   | 2--     | $\rho_2$ | $\omega_2$ | $\phi_2$ | $K_2^*$ |
| 2   | 3   | 3--     | $\rho_3$ | $\omega_3$ | $\phi_3$ | $K_3^*$ |

2.1. Quark Model vs Experiment

In the constituent quark model conventional mesons are bound states of a spin $\frac{1}{2}$ quark and a spin $\frac{1}{2}$ antiquark bound by a phenomenological potential which reflects the properties of QCD. The quark and antiquark spins combine to give total spin $\vec{S} = \vec{S}_q + \vec{S}_{\bar{q}} = 0, 1$ which is coupled to the orbital angular momentum $L$ to give states of total angular momentum $\vec{J} = \vec{L} + \vec{S}$ resulting in $J = L, L-1, L, L+1$. This leads to meson parity and charge conjugation given by

$$P = (-1)^{L+1} \quad \text{and} \quad C = (-1)^{L+S}$$

resulting in the meson states of Table 1.

A meson with $J^{PC} = 1^{--}$ would be forbidden in the constituent quark model and since quarks have charge either $+2/3$ or $-1/3$ a doubly charged meson, $m^{++}$, is also forbidden as a conventional meson state.

Since we cannot at this point calculate hadron properties from first principles we must rely on QCD motivated models to help interpret experimental resonances. Although there are many models in the literature the constituent quark model has the greatest success in describing hadron properties. In these models mesons are described by a Schrödinger equation

$$H = T + V_{q\bar{q}}$$

where $V_{q\bar{q}}$ is the effective quark-antiquark potential which consists of a spin-independent confining potential and spin-dependent terms. The confining potential is typically of the form:

$$H^{conf} = -\frac{4}{3} \frac{\alpha_s(r)}{r} + br$$

(3)
where the first term comes from one-gluon-exchange and the second term is the linear confining potential. The Coulomb piece dominates at short distance becoming more and more important with increasing quark mass while the linear piece dominates at large distance, becoming more important for the light quark mesons. This is illustrated in Fig. 1 where the rms radii of various mesons are indicated on a plot of a QCD motivated potential. One sees that mesons composed of the heavy $b$ quarks are relatively small and sit in the Coulombic region of the potential, while the lighter mesons sit in the linear region of the potential. Thus, the study of mesons constructed out of light quarks act as a probe of confinement.

The phenomenological spin dependent Hamiltonian is of the form:

$$H_{\text{spin}} = H_{ij}^{\text{hyp}} + H_{ij}^{s.o.(cm)} + H_{ij}^{s.o.(tp)}$$

where

$$H_{ij}^{\text{hyp}} = \frac{4}{3} \frac{\alpha_s(r)}{m_i m_j} \left\{ \frac{8\pi}{3} \vec{S}_i \cdot \vec{S}_j \cdot \delta^3(\vec{r}_{ij}) \right\}$$

is the colour hyperfine interaction,

$$H_{ij}^{s.o.(cm)} = \frac{4}{3} \frac{\alpha_s(r)}{r_{ij}^3} \left( \frac{1}{m_i} + \frac{1}{m_j} \right) \left( \frac{\vec{S}_i}{m_i} + \frac{\vec{S}_j}{m_j} \right) \cdot \vec{L}$$

is the spin-orbit colour magnetic piece arising from the one-gluon exchange and

$$H_{ij}^{s.o.(tp)} = -\frac{1}{2r_{ij}} \frac{\partial V(r)}{\partial r_{ij}} \left( \frac{\vec{S}_i}{m_i^2} + \frac{\vec{S}_j}{m_j^2} \right) \cdot \vec{L}$$
is the spin-orbit Thomas precession term where $V(r)$ is the interquark potential. In these formulae $\alpha_s(r)$ is the running coupling constant of QCD.

The colour hyperfine interaction is responsible for $^3S_1 - ^1S_0$ splitting in $\rho - \pi$, $K^* - K$, and $J/\Psi - \eta_c$. The spin-orbit and tensor piece of the hyperfine interaction break the degeneracy of the orbitally excited multiplets. The spin-orbit interaction has two contributions, $H_{ij}^{s.o.(cm)}$ and $H_{ij}^{s.o.(tp)}$. Since the hyperfine term is relatively short distance, it becomes less important for higher orbital excitations. Multiplet splittings then become a measure of the spin-orbit splittings, with contributions of opposite sign coming from the short range Lorentz vector one-gluon-exchange and the long range Lorentz scalar linear confinement potential. The ordering of states within a multiplet of given orbital angular momentum gives information on the relative importance of the two pieces. For example, for the $L=1$ strange meson multiplet, the quark model predicts $M(^3P_2) > M(^3P_1) > M(^3P_0)$, i.e. the $J = L + 1$ member of the multiplet is more massive than the $J = L - 1$ member. In contrast, for the $L = 4$ multiplet, the quark model predicts $M(^3G_3) > M(^3G_1) > M(^3G_5)$ so now the ordering is inverted with the $J = L - 1$ member more massive than the $J = L + 1$. The reason for this is that higher $L$ mesons have larger radii so the linear part of the potential is more important than the short distance Coulomb piece. Although the details of this inversion are model dependent, the inversion is a general property of QCD motivated potential models. Thus the multiplet splittings act as a probe of the confinement potential so that the study of excited light quark system, such as ones with high orbital angular momentum, provides information on non-perturbative QCD.

In what follows, for purposes of illustration, I will compare experimental data to the results of the particular model with which I am most familiar and which constitutes a comprehensive calculation of meson properties [8,9]. Let us start with the strange meson spectrum which is shown if Fig. 2. The spectrum is as rich as any in atomic physics with a beautiful regularity and numerous transitions, either electromagnetic transitions or strong transitions via $\pi$ or $\rho$ emission. There is good agreement for the masses of the leading orbital excitations which supports the picture of a linear confinement potential. The $^3S_1 - ^1S_0$ splitting is much smaller than the splitting between the $^3P_J$ centre of gravity and the $^1P_1$ state which is consistent with the expected properties of short distance one-gluon-exchange and a Lorentz scalar confining potential. A Lorentz vector confining potential would lead to comparable splittings for $^3S_1 - ^1S_0$ and $^3P_J - ^1P_1$. The information decreases as we go to the higher orbitally excited multiplets and for radial excitations. A similar pattern is obtained for the $s\bar{s}$ mesons except that they are even more sparsely mapped out than the strange mesons.

The status of of light meson spectroscopy is summarized in Fig. 3. Starting with the P-wave multiplets, which is the multiplet most filled, we find that even it is not well understood. The scalar mesons ($0^{++}$) are in a state of confusion due to the possible interpretation of the $a_0(980)$ and $f_0(980)$ as $g_{qq\bar{q}}$ states[10-12]. In the $1^{++}$ sector the $f_1(1420)$ has long been considered to be the $^3P_1$ $s\bar{s}$ meson. Recently the LASS group discovered another state [13] which appears a more likely candidate, the $f_1(1530)$. Finally, the $^1P_1$ $s\bar{s}$ state ($h'_1$) is yet to be confirmed. Turning to the higher mass multiplets, there is good agreement for the masses of the leading orbital excitations between the quark model and experiment supporting the picture of linear confinement.
Fig. 2. The level diagram for strange mesons. The wavy lines represent $\gamma$ emission, the solid lines represent $\pi$ emission and the dashed lines $\rho$ emission.
In general, however, the radially excited and orbitally excited mesons are even less understood than the P-waves. In particular, for the $s\bar{s}$ states there is very little known above the $L = 1$ multiplet. Some of my assignments (or lack of assignments) in Fig. 3 are subject to debate but this lack of a consensus underlines the fact that far too little is known about light meson spectroscopy. Without completing at least some of these multiplets we can hardly say we understand the meson spectrum.

2.2. Some Puzzles in Mesons

In addition to the obvious searches for the missing mesons there are numerous puzzles in meson spectroscopy which may be hints of new types of hadronic matter. I will only mention some of them here and refer the interested reader to other contributions and to the literature for a more detailed account [14-16].

The $\eta(1440)$ (formerly the $\iota(1440)$) is seen in the gluon rich $J/\psi$ radiative decay the $\iota$ and is therefore a prime candidate for a glueball [5]. It is now believed to be three separate states; two $0^{-+}$ and a $1^{++}$ [15]. Two isoscalar radially excited pseudoscalars ($2^1S_0$) are expected to lie in this mass region so until we obtain a more complete understanding of the $2^1S_0$ nonet the issue will remain cloudy. Another problem adding to the general confusion involves the misidentification of the $E(1420)$.

The $f_0(1750)$ (formerly the $\theta(1750)$) is also seen in $J/\psi$ radiative decay to $K\bar{K}$ making it another glueball candidate [5]. Although a number of $2^{++}$ states, both radially excited P-waves and orbitally excited F-waves are expected, none seem to fit the $\theta$. Further evidence for its exotic character is the fact that it was not seen in $K\bar{K}$ by the LASS group. Dooley, Swanson and Barnes speculate that the $\theta$ is a linear combination of loosely bound $K^*\bar{K}^*$ and $\omega\phi$ pairs [17].

The $f_1(1420)$ (formerly the E(1420)) has for a long time thought to be the $1^3P_1$ $J^{PC} = 1^{++} s\bar{s}$ meson. Recently the LASS group established the existence of another axial vector meson at about 1530 MeV which appears to be a much stronger candidate for this state [13]. If this is the case what is the E(1420)? and does this puzzle have anything to do with the the $\iota(1440)$ puzzle? Both states lie just above $K^*\bar{K}$ threshold and perhaps we are again seeing some manifestation of multiquark physics.

There are numerous puzzles besides the ones just mentioned. For instance what is the explanation of the $g_T$ $2^{++}$ tensor mesons seen at Brookhaven in $\pi p \rightarrow K\bar{K}$ [18]? Are they glueballs or are they conventional mesons or do they have a totally different explanation? Above, I mentioned that the $0^{++} \delta(980)$ and $S^*(980)$ mesons are thought to be $K\bar{K}$ molecules. If this is indeed the case where are the $3P_0$ $q\bar{q}$ states? Recently, candidates for the $3P_0$ $q\bar{q}$ states have been observed but they have yet to be confirmed.

There are clearly many puzzles remaining in meson spectroscopy which require both detailed experimental and theoretical study.

2.3. Hunting Missing States

Given our unsatisfactory knowledge of light meson spectroscopy how do we find the missing states and solve some of the puzzles? One can see from Fig. 3 that as we go to higher mass the number of states multiply rapidly so that in general we will have to find the missing states in a large background of other states. It is therefore highly unlikely that we will have any success in unravelling the spectroscopy by bump hunting.
Fig. 3. Summary of mesonic states with light quarks.
Rather, we will need high statistics experiments to perform partial wave analysis to filter by $J^{PC}$ quantum numbers. To assist us in this process a guide to the expected properties will be useful and we refer to quark model predictions for the expected masses and decay modes [8,9]. This can give us insight into why some states are missing and how to look for them. As an example of what such a search would entail we examine some missing states whose quark model predictions are listed in Tables 2 and 3.

Starting with the $\eta_2(1^D_2)$ we expect it to be almost degenerate in mass with its non-strange isoscalar partner, the $\pi_2$ (formerly the $A_3(1680)$). From Table 2 we see that it is expected to be rather broad and it decays predominantly through the $a_2$ isobar which in turn decays to $\rho\pi$. The final state is expected to have 4$\pi$'s making it rather complicated to reconstruct the original $\eta_2$ resonance. The $\rho_2(1^3D_2)$ will also decay dominantly to a 4$\pi$ final state. The $\omega_2$ decays to the simpler $\rho\pi$ final state with a moderate width but since it has a similar mass as the $\pi_2(1680)$ which also decays to $\rho\pi$ it is possible that it is masked by the $\pi_2$. The $s\bar{s}$ states, the $\eta_2'(1^D_2)$ and the $\phi_2(1^3D_2)$, are both relatively narrow and one would expect that they would have been observed. In fact the LASS group has recently reported seeing them in $K\bar{K}\pi$. The likely reason that they have been so difficult to find is that they are produced rather weakly.

The strange mesons, the $K_2^*(1^D_2)$ and the $K_2^*(1^3D_2)$ lie at around 1800 MeV. They decay to some relatively simple channels and are predicted to have a moderate width. It is possible that they have been sited as the $L(1770)$’s. The final state in the table is the broad $1^{--}\omega_1$. Structure has been seen in this mass region but the experimental situation is likely confused due to the nearby broad $2^3S_1$ $1^{--}$ state which is expected to lie at around 1450 MeV and overlaps and interferes with the $1^3D_1$ state.

One can perform a similar analysis of other multiplets. In Table 3 I give the expected properties of some orbitally and radially excited mesons. As listed, most of these states appear to be relatively narrow with dominant branching ratios to simple final states. There are candidates for several of these states. For example, an $f_2$ is observed with mass 1810 MeV, width $\sim 200$ MeV (with large uncertainties) and with $BR(f_2 \to \pi\pi) \sim 20\%$. Although the observed mass is consistent with the quark model predictions, the predicted width is at least a factor of two small. This discrepancy might be due to additional decay modes not considered in the analysis, which only includes two body modes, or it may reflect the sensitivity of the decay widths to the details of the meson wavefunction where a slight shift in the node of the $2P$ wavefunction or possibly mixing with nearby states, can have a large effect on the decay width. Similarly, the observed mass of the $K^*_2(1980)$ agrees with the quark model prediction and the decay properties are not inconsistent with the quark model ($\Gamma_{\text{theory}} \sim 150$ MeV vs $\Gamma_{\text{expt}} \sim 240$ MeV). Therefore, the predictions of Table 3 should be taken as a rough guide to the expected properties of radially excited P-wave mesons and until they are more fully tested against experiment they should not be taken too literally. In addition, there is a need for further theoretical work, to try to understand more complicated decay modes, and model dependent effects on the meson properties.

2.4. **Future Directions**

From the preceeding sections we conclude that we need a far better understanding of meson spectroscopy before we can say that we understand it and before we can
Table 2. Quark Model predictions for the properties of the missing L=2 mesons. The masses and widths are given in MeV. The masses come from Ref. 8 and the widths from Ref. 9.

| Meson State | Property | Prediction |
|-------------|----------|------------|
| $\eta_2(1^1D_2)$ | Mass | 1680 |
| | width | $\sim 400$ |
| | $BR(\eta_2 \to a_2\pi)$ | $\sim 70\%$ |
| | $BR(\eta_2 \to \rho\rho)$ | $\sim 10\%$ |
| | $BR(\eta_2 \to K^*K + c.c.)$ | $\sim 10\%$ |
| $\eta'_2(1^1D_2)$ | Mass | 1890 |
| | width | $\sim 150$ |
| | $BR(\eta'_2 \to K^*K + c.c.)$ | $\sim 100\%$ |
| $K_2(1^1D_2)$ | Mass | 1780 |
| | width | $\sim 300$ |
| | $BR(K_2 \to K^*f(1280))$ | $\sim 30\%$ |
| | $BR(K_2 \to \rho K)$ | $\sim 20\%$ |
| $\omega_1(1^3D_1)$ | Mass | 1660 |
| | width | $\sim 600$ |
| | $BR(\omega_1 \to B\pi)$ | $\sim 70\%$ |
| | $BR(\omega_1 \to \rho\pi)$ | $\sim 15\%$ |
| $K_2(1^3D_2)$ | Mass | 1810 |
| | width | $\sim 300$ |
| | $BR(K_2 \to K^*(1420)\pi)$ | $\sim 50\%$ |
| | $BR(K_2 \to K^*\pi)$ | $\sim 30\%$ |
| $\rho_2(1^4D_2)$ | Mass | 1700 |
| | width | $\sim 500$ |
| | $BR(\rho_2 \to [a_2\pi]_S)$ | $\sim 55\%$ |
| | $BR(\rho_2 \to \omega\pi)$ | $\sim 12\%$ |
| | $BR(\rho_2 \to \rho\pi)$ | $\sim 12\%$ |
| $\omega_2(1^3D_2)$ | Mass | 1700 |
| | width | $\sim 250$ |
| | $BR(\omega_2 \to \rho\pi)$ | $\sim 60\%$ |
| | $BR(\omega_2 \to K^*K)$ | $\sim 20\%$ |
| $\phi_2(1^4D_2)$ | Mass | 1910 |
| | width | $\sim 250$ |
| | $BR(\phi_2 \to K^*K + c.c.)$ | $\sim 55\%$ |
| | $BR(\phi_2 \to \phi\eta)$ | $\sim 25\%$ |
Table 3. Quark Model predictions for the properties of some of the N=2 P-wave mesons. The masses and widths are given in MeV. The masses come from ref. 8 and the widths from ref. 9.

| Meson State   | Property     | Prediction  |
|---------------|--------------|-------------|
| $a_2(2^3P_2)$ | Mass         | 1820        |
|               | width        | $\sim 140$ |
|               | $BR(a_2 \rightarrow \rho \pi)$ | $\sim 70\%$ |
|               | $BR(a_2 \rightarrow \eta \pi)$ | $\sim 10\%$ |
|               | $BR(a_2 \rightarrow K\bar{K})$ | $\sim 10\%$ |
|               | $BR(a_2 \rightarrow \eta'\pi)$ | $\sim 10\%$ |
|               | $BR(a_2 \rightarrow K^*\bar{K})$ | $\sim 10\%$ |
| $a_2(1^3F_2)$ | Mass         | 2050        |
| $f_2(2^3P_2)$ | Mass         | 1820        |
|               | width        | $\sim 90$  |
|               | $BR(f_2 \rightarrow \pi\pi)$ | $\sim 50\%$ |
|               | $BR(f_2 \rightarrow K\bar{K})$ | $\sim 20\%$ |
|               | $BR(f_2 \rightarrow K^*\bar{K})$ | $\sim 15\%$ |
| $f_2(1^3F_2)$ | Mass         | 2050        |
| $f_2'(2^3P_2)$| Mass         | 2040        |
|               | width        | $\sim 110$ |
|               | $BR(f_2' \rightarrow K\bar{K})$ | $\sim 35\%$ |
|               | $BR(f_2' \rightarrow \eta\eta)$ | $\sim 10\%$ |
|               | $BR(f_2' \rightarrow \eta'\eta)$ | $\sim 10\%$ |
|               | $BR(f_2' \rightarrow K^*\bar{K})$ | $\sim 43\%$ |
| $f_2'(1^3F_2)$| Mass         | 2240        |
| $K_2^*(2^3P_2)$| Mass     | 1940        |
|               | width        | $\sim 150$ |
|               | $BR(K_2^* \rightarrow K\pi)$ | $\sim 20\%$ |
|               | $BR(K_2^* \rightarrow K^*\pi)$ | $\sim 20\%$ |
|               | $BR(K_2^* \rightarrow \rho\bar{K})$ | $\sim 20\%$ |
| $K_2^*(1^3F_2)$| Mass     | 2150        |
exclude conventional interpretations of an exotic candidate with conventional quantum numbers. The first step is to find some of the missing states. It will be important to fill in both the orbitally excited multiplets and the radially excited multiplets. These missing states will lie in a large background of other states. To find them, results from the LASS spectrometer group show us that we will need unprecedented statistics along with a partial wave analysis to filter the $J^{PC}$ quantum numbers.

We will also need to develop new experimental and theoretical techniques to study broad resonances. From the experimental side it is clear that it will not be easy to identify a broad resonance in a background of other broad resonances and in the presence of new production thresholds. From the theoretical side most quark model calculations have treated mesons in the valence quark limit without considering the influence of coupling to production and decay channels. We are at the point in our understanding that these effects can no longer be ignored as they can make significant changes to the observed hadron masses and decay properties. These effects are starting to be examined by Barnes, Swanson, and Weinstein [19,20]. In addition, we can no longer ignore final state interactions. Some progress has been made on this problem by Barnes and Swanson [21]. It will be necessary to understand how to obtain observed cross sections starting with the underlying spectrum when decay channel coupling is taken into account along with final state interactions of the decay products.

3. **Gluonic Excitations** [5]

The complication in QCD which makes it so difficult to solve is the presence of boson-boson interactions required by gauge invariance which in perturbation theory gives rise to rather complicated three and four-boson couplings. Although it is difficult to extract physical properties from the QCD Lagrangian it is these gluon self couplings which lead to the belief that gluons play a dual role in QCD; as mediators of the strong force as in the conventional $q\bar{q}$ mesons and $qqq$ baryons, and as constituents in glueballs and hybrids. The problem at present is that it is not even clear what the correct degrees of freedom are for soft QCD so that the predictions of the different models must be viewed with caution. Nevertheless, the discovery of glueballs or hybrids would be an important advance in our understanding QCD in the “soft” region.

In searching for glueballs and hybrids there are two ways of distinguishing them from conventional states:

1. To look for an excess of observed states over that predicted by the quark model. For this method to succeed we need a very good understanding of conventional mesons so that we can rule out a conventional interpretation of a newly found state. The previous section has shown the difficulties of this approach given our incomplete knowledge of conventional mesons and the general confusion in the 1.5 to 2.5 GeV mass region.

2. Search for exotic quantum numbers which would signal states that cannot be conventional quark model states.

Both approaches require a knowledge of expected glueball and hybrid properties which we will examine in what follows.
We begin by sketching out two models of soft QCD whose results we will use in what follows. The qualitative differences of these models stresses our ignorance of the low $Q^2$ regime of QCD.

3.1. The Bag Model [22-26]

In the bag model [26] hadrons are viewed as a region of space enclosing a fixed number of quarks and gluons with the model made Lorentz invariant by the addition of a surface pressure term, $B_0$, to the Lagrangian density. Inside the bag the quark fields, $\psi$, obey the free Dirac equation along with the boundary conditions that; 1) there is no colour current through the bag surface (S), and 2) pressure balance determines the bag surface.

\[(\not{\mathcal{D}} - m)\psi = 0 \quad \text{inside } S \]
\[\psi = 0 \quad \text{outside } S \quad (8)\]

The lowest energy solutions have quarks in $1S_{1/2}$, $1P_{1/2}$, $1P_{3/2}$ eigenmodes. Gluons in the Bag obey the free Helmholtz equation subject to the same boundary conditions.

\[(\nabla^2 + \omega^2)A^a = 0 \quad \text{inside } S \]
\[A^a = 0 \quad \text{outside } S \quad (9)\]

The solutions are the transverse electric (TE) and transverse magnetic (TM) cavity resonator modes with $J^{PC} = 1^{+-}$ and $J^{PC} = 1^{--}$ respectively. In the zeroth order bag model, the mass of a hadron is simply the sum of the quark and gluon constituent energies and the energy of the bag itself. To go beyond the zeroth order bag model involves including contributions from gluon exchange [22,23].

3.2. The Flux Tube Model

The flux tube model of hadrons [27,28] is based on the strong coupling limit of QCD [29] with its parameters fixed from the familiar meson and baryon sectors. The significant difference between the flux tube approach and the bag model approach is that the eigenstates of the strong coupling limit of (lattice) QCD consist of, not quarks and gluons as in the bag model, but quarks on lattice sites connected by arbitrary paths of flux links or in the absence of quarks, of arbitrary closed loops of flux (glueloops). It is assumed that the flux tube picture survives departures from the strong coupling limit or in other words, that the flux tubes do indeed form a reasonable set of basis states, and that the adiabatic treatment of the flux tubes in the presence of quark motion is reasonable.

In this picture the string states define adiabatic quark potentials analogous to the nuclear potentials in molecular physics where adiabatic surfaces are defined for the nuclear motion based on the faster moving electronic potentials. We should then expect a tower of quark states built on each string adiabatic surface. This is illustrated pictorially in Fig. 4. In the flux tube model conventional hadrons correspond to gluonic fields in the ground states.
3.3. Pure Glue States

Both the bag model and flux tube model expect that hadrons will exist with no valence quark content at all. The predictions for glueball masses vary considerably from calculation to calculation. I use the flux tube model predictions as a guide because of their agreement with lattice calculations [29,30]. These are shown in Fig. 5. The flux tube model predicts that the lowest glueloop (glueball) is a $0^{++}$ at 1.5 GeV with all other states above 2 GeV and the lowest $J^{PC}$ exotic at around 2.5 GeV. For comparison, the bag model predictions are considerably lower with $M_{0^{++},2^{++}} = 1$ GeV, $M_{0^{++},2^{++}} = 1.6$ GeV, and $M_{0^{-+},2^{++}} = 1.3$ GeV. Because of the uncertainty in the scalar meson sector it seems likely that it would be very difficult to distinguish a scalar meson from the poorly understood conventional mesons[^]. More generally, it will be difficult to unambiguously determine that any state with conventional quantum numbers is a glueball due to the dense background of conventional mesons. The best bet will then be to find glueballs with exotic quantum numbers. Unfortunately these states are all expected to have mass greater than 2.5 GeV and so will be difficult to find. In addition, from the CEBAF point of view, glueballs are not expected to couple strongly to either photons or vector mesons so are likely to be difficult to produce at CEBAF. Glueballs therefore do not seem to be the best place to start our search for gluonic hadrons.

3.4. Hybrid Mesons

From our previous discussion it appears that the most fruitful method to search for hybrids is to search for states with quantum numbers inconsistent with quark model predictions.

[^] Although the excess of scalar mesons beyond the quark model predictions is seen as evidence for glueballs in this sector.
Fig. 5. The low lying glueball mass spectrum. The flux tube results come from ref. 27 and the lattice results from ref. 31.
The first step in this approach is to enumerate the hybrid $J^{PC}$ quantum numbers. To do this in a model independent manner obeying gauge invariance we form gauge invariant operators [32,33] from a colour octet $q\bar{q}$ operator and a gluon field strength.

$$O = (\bar{\psi} \Gamma^{a} \psi) \otimes (\vec{E}^{a} \text{ or } \vec{B}^{a}) \quad (10)$$

The resulting composite operator, known as an interpolating field, is equally applicable to all approaches, from the Bag-model to the flux tube model in addition to more rigorous lattice gauge theory calculations. For example the interpolating field for the $1^{-+}$ state is given by $(\bar{\psi} \vec{\gamma} \psi) \times \vec{B}$ and for the $2^{+-}$ by $(\bar{\psi} \gamma_{5} \vec{\gamma} \gamma_{5} \psi) \otimes \vec{B}$. The quantum numbers of the low lying hybrids are given by:

\[
\begin{array}{cccc}
2^{++} & 2^{-+} & 2^{++} & 2^{--} \\
1^{++} & 1^{-+} & 1^{++} & 1^{--} \\
0^{++} & 0^{-+} & 0^{++} & 0^{--}
\end{array}
\]

Higher $J$ operators can also be constructed but presumably they are higher in mass and more difficult to produce. The underlined $q\bar{q}g$ states have exotic quantum numbers not present in the constituent quark model. If these exotic states are sufficiently low in mass and do not have exceedingly large widths they could provide the smoking gun evidence for hybrids which we are seeking: Their discovery would unambiguously signal hadron spectroscopy beyond the quark model.

3.4.1. Hybrid Masses

**Bag Model Predictions:** To make hybrids we combine a colour octet gluon with a $q\bar{q}$ pair in a colour octet to obtain a colour singlet:

$$(q\bar{q})_{8} \times g_{8} = (q\bar{q}g)_{1} + \ldots.$$ 

The lowest $q\bar{q}g$ hybrid meson multiplets are constructed from a colour octet $q\bar{q}$ with $J^{PC} = 0^{-+}$ or $1^{--}$, each in the $J^{PC} = (1/2)^{+}$ mode, and a gluon in the lightest TE mode with $J^{PC} = 1^{+-}$ resulting in the following lowest lying hybrids;

$$2^{-+}, 1^{-+}, 1^{--}, 0^{++}.$$ 

The SU(3) flavour quantum numbers of a hybrid are those of the component $q\bar{q}$ pair so that hybrid mesons span the familiar SU(3) flavour nonets. However, the I=0 and I=1 states are not degenerate because in the isoscalar hybrids, the relative ease of internal annihilation of the $q\bar{q}$ pair which is already in a colour octet, shifts the mass.

Some representative results of bag model calculations of the hybrid spectrum which include spin-dependent forces due to gluon exchange [22-24] are shown in Fig. 6 along with constituent quark model predictions for conventional mesons. Different calculations are in reasonable agreement for the splittings but differ on the multiplet mass. The $0^{-+}$, $2^{-+}$, and $1^{--}$ hybrid nonets are near in mass to $q\bar{q}$ states with the same quantum numbers which can result in considerable mixing. This can only confuse the situation when determining if a state is a hybrid or conventional meson. Thus, the discovery of such states would be difficult to be convincing because they are also candidates for conventional states.
Fig. 6. Hybrid mass predictions. The short dashed lines are the bag model predictions of Barnes Close and deViron, ref. 22. The shaded region are the bag model predictions of Chanowitz and Sharpe for a range of values of the quark and gluon self energies, ref. 23. The long dashed lines are the flux tube model predictions of Isgur and Paton, ref. 27. The solid lines are the conventional $q\bar{q}$ predictions of the relativized quark model, ref. 8.
Flux Tube Model Predictions: There are two types of hybrids in this model, vibrational hybrids which correspond to excitations of the quantum string into higher string normal modes, and topological hybrids which have more complicated string topologies and correspond to higher energy adiabatic surfaces. The latter are expected to be much higher in energy so we will not discuss them further.

The adiabatic potentials are characterized by mode occupation numbers with a polarization index and a string mode index. The first excited state is doubly degenerate with phonons of transverse vibration with $\sigma = \pm 1$ angular momentum about the $q \bar{q}$ axis. When combined with spin we get the 8 nearly degenerate nonets of hybrid mesons:

$$J^{PC} = 0^{\pm \mp} \ 1^{\pm \mp} \ 2^{\pm \mp} \ 1^{\pm \pm}$$

with masses approximately $1.9 \pm 0.1$ GeV for hybrids with no strange quark content. Among these states are three $J^{PC}$ exotic nonets with nine neutral members having $J^{PC} = 2^{+-}, 1^{+-},$ and $0^{+-}$. These results should be contrasted to the bag model where there is no such degeneracy because the TM mode is much higher in mass than the TE mode. These results are compared to bag model results in Fig. 6.

3.4.2. Hybrid Decays

In the previous section we came to the conclusion that the most promising approach for finding hybrids is to look for ones with exotic quantum numbers. Even so, there are numerous states to consider so, for the sake of brevity, we take the $\hat{\rho}$ and $\hat{\phi}$ $1^{-+}$ exotics as examples. Possible decays are given by:

$$\hat{\rho} \rightarrow [\pi \eta, \pi \eta', \pi \rho, K^* \bar{K}, \eta \rho, \ldots]_P$$
$$\rightarrow [\pi b_1, \pi f_1, \eta a_1, K K_1 \ldots]_S$$
$$\hat{\phi} \rightarrow [\eta \eta', k \bar{K}(1400), K^* \bar{K}, \ldots]_P$$
$$\rightarrow [\bar{K} Q_2]_S$$
$$\rightarrow [\bar{K} Q_1]_D$$

The underlined decays to two distinct pseudoscalars in a relative P-wave is a unique signature of the $1^{-+}$ state.

Given this long list of decays we turn to the various models for guidance to which modes are likely to be dominant. One would naively expect S-wave mesons in the $\pi \eta$ or $\pi \rho$ channels to be dominant due to the large available phase space. However, a common feature of the various models is the selection rule that the gluonic excitation cannot usually transfer its angular momentum to the final state meson pairs as relative angular momentum but must instead appear as internal orbital angular momentum of the $q \bar{q}$ pairs.\footnote{I note however, that this selection rule does not appear to be absolute.} This eliminates $\pi \eta$, $\pi \rho$, $\pi \eta'$, $\eta \rho$, $\eta \eta'$, and $K^* \bar{K}$. The selection rule suppresses the decay channels which would likely be large and may make hybrids stable enough to appear as conventional resonances while at the same time explaining why hybrids with exotic $J^{PC}$ have yet to be seen; they do not couple strongly to simple final states.
In particular, in the Bag model the dominant decays occur when the valence gluon forms a colour octet $J^{PC} = 1^{--}$ $q\bar{q}$ pair in which either $q$ or $\bar{q}$ is in a P-wave mode. The bag then contains two $q\bar{q}$ colour octets which after rearrangement fall apart into $q\bar{q}$ singlets, one in an S-wave ground state with $J^{PC} = 0^{++}, 1^{--}$ and the other in an L=1 $J^{PC} = (0, 1, 2)^{++, 1^{++} -}$. I.e. $J^{PC} = 1^{++} \rightarrow \pi f_1$ or $\eta a_1$.

The flux tube model also predicts that the low lying hybrids will decay preferentially to final states with one ground state S-wave and one excited P-wave meson; $b_1(1235)\pi, a_2(1320)\pi, K_2^*(1420)\bar{K}, \pi(1300)\pi, \ldots$, rather than two ground state mesons like $\pi\pi, \rho\pi, K\bar{K}$. The reason for this is that the relative coordinates of the two final state mesons are parallel to the initial meson axis and so cannot absorb the unit of string angular momentum about the initial meson axis. Hence the string angular momentum is absorbed as an internal meson orbital angular momentum and the selection rule is broken for final states with different spatial wavefunctions [34]. The flux tube model expects stronger coupling to final states with one S-wave and one P-wave final state meson.

The flux tube model predictions are listed in Table 4. The flux tube model predicts that the $\hat{a}_2, \hat{a}_0$, and $\hat{f}_0'$ are probably too broad to appear as resonances. The $\hat{w}_1$ decays mainly to $[a_1(\pi)]_S$ and $[\pi(1300)\pi]_P$ with $\Gamma \sim 100 \text{ MeV}$ which would make it difficult to reconstruct the original hybrid given the broad widths of the final state mesons. Similar problems also make the $\hat{\phi}_1$ difficult to find. According to the flux tube model the best bets for finding hybrids are: $\hat{\rho}_1, \hat{f}_2, \hat{f}_0$, and $\hat{f}_2'$.

What we conclude from all this is that the favoured final states all contain broad P-wave mesons. To reconstruct the original resonance an isobar analysis will be essential and to do this we will again need unprecedented statistics to pull a signal from the background.

4. Multiquark States

Multiquarks are discussed in detail in the contribution of Weinstein [20]. Here I comment briefly on some points relevant to meson spectroscopy. Upon considering $qq\bar{q}\bar{q}$ systems we find that the colour couplings are not unique as they are in mesons and baryons and whether or not multiquark states exist is a dynamical question. It is possible that multiquark states exist as bound states [35] but it is also possible that $qq\bar{q}\bar{q}$ configurations lead to meson-meson potentials [12]. Both must be taken into account when attempting to unravel the meson spectrum.

A study of the $J^{PC}$ sector of the $qq\bar{q}\bar{q}$ system found that weakly bound $K\bar{K}$ “molecules” exist in the isospin zero and one sectors in analogy to the deuteron. It was suggested that these two bound states be identified with the $f_0(975)$ and $a_0(980)$ (the $S^*$ and $\delta$). The meson-meson potentials which come from this picture, when used with a coupled channel Schrodinger equation, reproduce the observed phase shifts for the $\delta$ and $S^*$ in $\pi\pi$ scattering [12]. The $K\bar{K}$ molecules are the exception however, as the model predicts that in general the $qq\bar{q}\bar{q}$ ground states are two unbound mesons.

There is evidence that meson-meson potentials must be considered in other processes as well. In the reaction $\gamma\gamma \rightarrow \pi^+\pi^-$ the meson-meson potentials are needed along with $q\bar{q}$ resonances to reproduce the $\gamma\gamma \rightarrow \pi^+\pi^-$ cross section data [36]. Enhancements in the production of low invariant mass $\pi\pi$ pairs have been observed in a number of
Table 4. The dominant decays of the low-lying exotic hybrid mesons. From ref. 28.

| Hybrid State | Decay Mode | L of Decay | Partial Width (MeV) |
|--------------|------------|------------|---------------------|
| $\hat{a}_2^{+-}(1900)$ | $[\pi a_2]_P$ | $\pi a_1]_P$ | $\pi h_1]_P$ | 450 |
| $\hat{f}_2^{+-}(1900)$ | $[\pi h_1]_P$ | 150 |
| $\hat{f}_2^{++}(2100)$ | $[K K^* + c.c.]_P$ | 250 |
| $\hat{\omega}_1^{--}(1900)$ | $[\pi a_1]_{S,D}$ | 100,70 |
| $\hat{\phi}_1^{+-}(2100)$ | $[\pi a_1]_{S,D}$ | 100 |
| $\hat{\rho}_1^{+-}(2100)$ | $[\pi a_1]_{S,D}$ | 100, 30 |
| $\hat{\phi}_0^{++}(2100)$ | $[K Q_2 + c.c.]_P$ | 200 |
| $\hat{a}_0^{+-}(1900)$ | $[\pi a_1]_{S,D}$ | 100,70 |
| $\hat{f}_0^{+-}(1900)$ | $[\pi a_1]_{S,D}$ | 100,70 |
| $\hat{f}_0^{++}(2100)$ | $[\pi a_1]_{S,D}$ | 100,70 |
| $\hat{a}_0^{++}(1900)$ | $[K Q_2 + c.c.]_S$ | 250 |
| $\hat{f}_0^{++}(2100)$ | $[K Q_2 + c.c.]_S$ | 250 |
| $\hat{f}_0^{++}(2100)$ | $[K Q_2 + c.c.]_S$ | 250 |


processes; \( \eta' \rightarrow \eta \pi \pi, \psi' \rightarrow J/\psi \pi \pi, \Upsilon(nS) \rightarrow \Upsilon(mS) \pi \pi \), and \( \psi \rightarrow \omega \pi \pi \). Similar enhancements have also been seen in some \( K \pi \) channels in \( \bar{p}p \rightarrow K \bar{K} \pi \). The conclusion drawn from these examples is that final state interactions arising from meson-meson potentials will play a central role in understanding the 1 to 3 GeV mass region. So far only pseudoscalar mesons in the final state have been considered so the next logical step is to extend the analysis to vector-vector and pseudoscalar-vector channels. Perhaps these multiquark effects are the key to the \( E/\eta \) and \( \theta \) puzzles.

5. Meson Spectroscopy at CEBAF

CEBAF offers a number of possibilities for studying meson spectroscopy using high intensity photon beams incident on nuclear targets. Using the CEBAF electron beam high energy photons can be produced by either bremsstrahlung through a thin radiator or backscattering a high powered laser from the incident electron beam (a “Compton Collider”). The resulting photon energy will be close to the original beam energy resulting in center of mass energies ranging from \( \sim 4 \) GeV for an 8 GeV electron beam to \( \sim 4.8 \) GeV for a 12 GeV incident electron beam. The photons can be used to photoproduce meson resonances covering the poorly explored region of 2 to 4 GeV where many conventional and non-conventional mesons are expected to lie. In particular, the lowest lying hybrid mesons which are expected at around 2 GeV.

The basic production mechanism is that, through vector meson dominance, the photon has vector meson components such as the \( \rho \), \( \omega \), and \( \phi \) so that the nucleon target is interacting with the vector meson component of the photon. There are numerous ways that the vector meson can then interact with the nucleon target to produce excited final state mesons which differ primarily by the t-channel exchange mechanism. These are illustrated in Fig. 7. Excited states can be produced via diffraction — the exchange of a (colourless) pomeron; inelastic production where the original target nucleon is excited into, say, an \( N^* \); and charge exchange where a charged pion is exchanged in the t-channel so that the target nucleon is excited into, for example, a \( \Delta^{++} \). In addition, the photon can interact as a photon through Primakof production where, the photon excites a t-channel \( \pi \) to produce the final state meson. Finally, the photon can interact with a t-channel photon to produce a final state resonance via two photon fusion. Taken together CEBAF offers a wide range of complementary production mechanisms which can help decipher the underlying meson structure.

Because the photons have a relatively large \( s \bar{s} \) content they are a good source of strangeonium states. Because the \( s \)-quark is intermediate in mass between the heavier \( c \) and \( b \) quarks where we believe that quark potential models are reasonable approximations to QCD and the lighter \( u \) and \( d \) quarks where relativistic effects make the naive quark models suspect, strangeonium spectroscopy provides a useful bridge between these two extremes. Thus, CEBAF can add considerably to our knowledge of both the radially excited and orbitally excited strangeonium states which are important for our understanding of soft QCD.

In addition, it has been speculated that photoproduction experiments are a good place to search for hybrids [28]. The basic idea is that the glue in the vector mesons is excited by the t-channel particle exchange to produce a hybrid meson. However, detailed calculations of this production mechanism do not presently exist and are only
In summary, CEBAF offers some interesting production mechanisms for mesons. With the extremely high intensity of the electron beam, and hence of the photon beam it offers the possibility of the very high statistics needed for the next generation of meson spectroscopy experiments. It may turn out that CEBAF will be the long awaited KAON factory.

6. Final Comments

I hope I have demonstrated that meson spectroscopy is an extremely rich subject with fundamental unanswered questions. Our present knowledge of hadron spectroscopy is a very shaky foundation on which to base our understanding of QCD. At present it is not even clear what the relevant degrees of freedom are for describing this regime of QCD. The first step to understanding soft QCD is to find the missing conventional $q\bar{q}$ states. Until we understand conventional hadrons better it will be very difficult to make progress in finding evidence for the gluonic degree of freedom in the hadron spectrum which is the outstanding issue.

Although it is conceivable that hybrid states with non-exotic quantum numbers could be identified as being excess states beyond those predicted by the quark model, given the very broad range of predictions for hybrid masses, I very much doubt that this is the most fruitful approach. It is more likely that, to be successful, a hybrid search should focus on the exotic properties of hybrids which would offer unambiguous
evidence of new physics. The most uncontroversial such characteristic is that all models agree that one of the lowest hybrids will have exotic $J^P_C$ quantum numbers $1^{-+}$ with mass about $1.6 \pm 0.3$ GeV. The presence of a resonance signal in this channel would be strong evidence for the discovery of a hybrid so it seems sensible that this be the place to begin any experimental search.

One should appreciate that the study of $q\bar{q}$, hybrids, glueballs, and $qq\bar{q}\bar{q}$ is an indivisable subject since they are all governed by the same theory — QCD, and require the same experiments. To unravel the meson spectrum in the 1 to 3 GeV mass region will take unprecedented statistics. It is important that many hadron properties be studied in many different channels. CEBAF has an important role in meson physics. Because of the high $s\bar{s}$ content of the photon it will be able to produce large numbers of $s\bar{s}$ states significantly improving our incomplete knowledge of this sector. CEBAF also offers the possibility of discovering hybrid mesons which would provide evidence for gluonic excitations in mesons.

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