Topics in Meson Spectroscopy *

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In this mini-review I discuss three topics in meson spectroscopy. The production of heavy quarkonium states, S-wave scattering below 1 GeV, and exotic hybrid meson production. This is not intended to be a comprehensive review, just an overview of several topics of current interest.

1. INTRODUCTION

Meson spectroscopy is an extremely broad subject, covering $\pi\pi$ scattering with $\sqrt{s} < 1$ GeV to the heaviest $b\bar{b}$ states with masses greater than 10 GeV \cite{1,2}. The goal at both ends of the energy scale is to understand QCD in the nonperturbative regime. It is impossible to do justice to such a large body of work in a short talk so I restrict myself to a few selected topics. Many other aspects of meson spectroscopy are covered in other contributions where the interested reader can obtain a more balanced view of recent developments.

In a very short period of time, the subject of heavy quarkonium has come to the forefront. This is the result of two recent developments; the CLEO collaboration is taking data at the $\Upsilon(3S)$ and $\Upsilon(2S)$ which will exceed the world’s existing data by a large factor and the B-factories have observed a number of charmonium states in B-decay \cite{3,4,5} culminating in the discovery of the $\eta_c'$ in $B \rightarrow \eta_c'K$ by the Belle collaboration \cite{3}. These measurements have led to the hope that some of the missing charmonium states may also be observed in B decay. Simultaneously, there has been great progress in Lattice QCD \cite{6} so that we have progress on both the experimental and theoretical fronts.

On a second front there continues to be vigorous discussion about the structure seen in $\pi\pi$ S-wave scattering below 1 GeV. My impression is that a consensus is emerging among workers in the field with respect to general features. However, there continues to be considerable debate about the details. Low energy S-wave scattering is discussed in Section 3.

Finally, one of the most important topics in meson spectroscopy is the issue of gluonic excitations. To highlight this topic I briefly describe a proposal that should make a definitive statement about the existence of these objects and map out their properties.

2. HEAVY QUARKONIUM

The discovery of a D-wave $b\bar{b}$ state by the CLEO collaboration \cite{7} and the discovery of the $\eta_c'$ in B-decay by the BELLE collaboration \cite{3} represent important advances in heavy quarkonium physics. With continued running by CESR on the $\Upsilon(2S)$ and $\Upsilon(3S)$, large samples of B-mesons being collected by the B-factories, and future measurements at CLEO-c/CESR-c, I anticipate further discoveries in the near future. At the same time, advances in Lattice QCD calculations of the heavy quarkonium spectra are leading to quantitative predictions which need to be tested against experiment \cite{6}. Taken together we should expect a much better understanding of heavy quarkonium from first principles QCD.

Numerous $b\bar{b}$ states are expected to exist below the $B\bar{B}$ decay threshold. However, only spin triplet states have been observed in the $b\bar{b}$ system and only 2 spin-singlet states have been observed in $c\bar{c}$. Given that there is a wide variation of the spin dependent splittings predicted by various calculations, the observation of addi-
tional quarkonium states, including the missing spin-singlet states, would pose an important test of the calculations (comparisons are given in Ref. [8,9,10]). Similarly, various calculations predict different values for the mass of $b\bar{b}$ D-wave cog (the spin weighted mass of the triplet states). Observation of these states would be a powerful discriminator of the various calculations.

CESR/CLEO has just completed a high statistics data taking run at the $\Upsilon(3S)$ and will soon be running at the $\Upsilon(2S)$. We expect that analysis of the data will yield a rich spectroscopy. To give direction to searches we use the quark model to estimate radiative widths and branching ratios.

2.1. D-Wave States

There are several strategies to search for D-wave mesons [8]. The first is via direct scans in $e^+e^-$ collisions to produce the $^3D_1$. However, given the small coupling of the $^3D_1(b\bar{b})$ to the photon and the effects of line smearing this approach would require substantial statistics. A second approach is via the electromagnetic cascades $\Upsilon(3S) \rightarrow \gamma \chi_{b}^{'} \rightarrow \gamma \gamma^3D_J$. Using quark model estimates of both E1 dipole transitions and decays to final state hadrons [8] we estimate the number of events for 4$\gamma$ cascades that proceed via various intermediate states [8]. These are given in Table 1. We expect $\sim 38$ events per $10^6 \Upsilon(3S)$'s to be produced via $^3D_J$ states. Backgrounds can be reduced using the $\Upsilon \rightarrow e^+e^- + \mu^+\mu^-$ final states as event tags. A substantial background will be 4$\gamma$ cascades proceeding via the $^3S_1$ state which will also produce $\sim 38$ events per $10^6 \Upsilon(3S)$'s. These events can be separated from the $^3D_J$ intermediate state using the fact that the energies of the intermediate photons are different. The CLEO collaboration successfully employed this strategy for the first observation of a triplet $\Upsilon(1D)$ state which was announced at this conference [8].

| 2$^3P_J$ state | Next state | $1^3P_J$ | Events |
|----------------|------------|----------|--------|
| $2^3P_2$      | $1^3D_2$   | $1^3P_2$ | 7.8    |
| $1^3D_2$      | $1^3P_1$   |          | 0.3    |
| $1^3D_1$      | $1^3P_2$   |          | 0.0    |
|                | $1^3P_1$   |          | 0.1    |
|                | $1^3P_0$   |          | 0.0    |
| $2^3S_1$      | $1^3P_2$   |          | 4.1    |
|                | $1^3P_1$   |          | 8.8    |
|                | $1^3P_0$   |          | 0.4    |
| $2^3P_1$      | $1^3D_2$   | $1^3P_2$ | 2.5    |
|                | $1^3P_1$   |          | 20.1   |
| $1^3D_1$      | $1^3P_2$   |          | 0.1    |
|                | $1^3P_1$   |          | 3.3    |
|                | $1^3P_0$   |          | 0.4    |
| $2^3S_1$      | $1^3P_2$   |          | 7.5    |
|                | $1^3P_1$   |          | 15.9   |
|                | $1^3P_0$   |          | 0.7    |
| $2^3P_0$      | $1^3D_1$   | $1^3P_2$ | 0.0    |
|                | $1^3P_1$   |          | 0.3    |
|                | $1^3P_0$   |          | 0.0    |
| $2^3S_1$      | $1^3P_2$   |          | 0.3    |
|                | $1^3P_1$   |          | 0.7    |
|                | $1^3P_0$   |          | 0.0    |

2.2. $\eta_b(nS)$ States

$\eta_b(nS)$ can be produced via magnetic dipole (M1) transitions $\Upsilon(nS) \rightarrow \eta_b(n'S) + \gamma$ [8]. The rates for magnetic dipole transitions in quarkonium ($Q\bar{Q}$) bound states are given in the nonrelativistic approximation by

$$\Gamma(3S_1 \rightarrow ^1S_0 + \gamma) = \frac{4}{3} \alpha \frac{e_Q^2}{m_Q^2} |\langle f|j_0(kr/2)|i\rangle|^2 \omega^3(1)$$

where $\alpha$ is the fine-structure constant, $e_Q$ is the quark charge in units of $|e| (-1/3$ for $Q = b$), $m_Q$ is the quark mass (which we take equal to 4.8 GeV/$c^2$) and $k$ ($\omega$) is the emitted photon’s momentum (energy). The available phase space for allowed transitions (the principal quantum number is unchanged) is small leading to a small partial width. In contrast, the hindered transitions (the principal quantum number changes)
have large available phase space. In the nonrelativistic limit the overlap integral for hindered transitions is zero due to the orthogonality of the initial and final wavefunctions. However, relativistic corrections from the hyperfine interaction leads to differences in the $S$-states. The branching ratios for $\Upsilon(nS) \rightarrow \eta_b(n'S)\gamma$ are given in Table 2. Note that the radiative widths are quite sensitive to model dependent details. From these predictions we expect $\eta_b$'s to be produced at a substantial rate. Another possible production channel for $\eta_b$'s is the process $\Upsilon(3S) \rightarrow h_b(1P_1)\pi\pi \rightarrow \eta_b + \gamma + \pi\pi$. The BR for $\Upsilon(3S) \rightarrow h_b(1P_1)\pi\pi$ is expected to be 0.1-1% while the BR for $h_b(1P_1) \rightarrow \eta_b + \gamma$ is estimated to be $\sim 50\%$.

2.3. Production of $^1P_1$ States

We consider two types of cascades to produce the $^1P_1$ $c\bar{c}$ and $b\bar{b}$ states [10]. The first starts with an $\Upsilon(3S)$ or $\psi(2S)$ produced in $e^+e^-$ annihilation which then underdoes an M1 transition to the $\eta(2S)$ state followed by an E1 transition to the $h(1P_1)$ state and a final E1 transition to the $\eta(1S)$ state:

$$\Upsilon(3S) \rightarrow \eta_b(2S) + \gamma \rightarrow h_b + \gamma\gamma \rightarrow \eta_b + \gamma\gamma\gamma$$ (2)

$$\psi(2S) \rightarrow \eta_c(2S) + \gamma \rightarrow h_c + \gamma\gamma \rightarrow \eta_c + \gamma\gamma\gamma$$ (3)

The second cascade consists of the single pion emission transition from the initial $^3S_1$ state followed by an E1 transition to the $\eta(1S)$:

$$\Upsilon(3S) \rightarrow h_b + \pi \rightarrow \eta_b + \gamma + \pi$$ (4)

$$\psi(2S) \rightarrow h_c + \pi \rightarrow \eta_c + \gamma + \pi$$ (5)

To determine if either of these cascades is promising we need the appropriate branching ratios and hence the partial widths. In the quark model they are given by:

$$\Gamma(1^1S_0 \rightarrow 1^3P_1 + \pi + \gamma) = \frac{4}{3}\alpha e^2_Q \omega^3 |\langle 1^1P_1|\pi|1^3S_0\rangle|^2$$ (6)

so that $\Gamma[\eta_b(2S) \rightarrow h_b(1P) + \gamma] = 2.3 \text{ keV}$. In addition we need the hadronic widths for the $\eta_b(2S)$. There are considerable theoretical uncertainties which to a large extent can be reduced by relating ratios of theoretical expressions to observed hadronic widths. For the $\eta_b(2^{1}S_0)$ we take

$$\Gamma[1^1S_0 \rightarrow gg] = \frac{27\pi}{5(\pi^2 - 9)} \times \Gamma[3^3S_1 \rightarrow ggg]$$ (7)

where 1st order QCD corrections are included in our numerical results but are not explicitly shown. This gives $\Gamma[\eta_b(2^{1}S_0) \rightarrow gg] = 4.1 \pm 0.7 \text{ MeV}$. Combining the resulting branching ratios for $\Gamma[\Upsilon(3S) \rightarrow \eta_b' + \gamma]$ and $\Gamma[\eta_b' \rightarrow h_b + \gamma]$ gives $\Gamma[\Upsilon(3S) \rightarrow \eta_b'\gamma \rightarrow h_b\gamma\gamma] = 2.6 \times 10^{-7}$. This would result in only 0.3 events per $10^6 \Upsilon(3S)$'s. A similar exercise yields $\Gamma[\psi(2S) \rightarrow \eta_c\gamma \rightarrow h_c\gamma\gamma] = 10^{-6} - 1$ event per $10^6 \psi's$.

A more promising approach utilizes the hadronic decay $\Upsilon(3S) \rightarrow \pi^+\pi^-P_1$ which is estimated to have a BR of around $0.1\%$ [13]. Again we need to estimate the radiative and hadronic widths of the $^1P_1$ states:

$$\Gamma[1^1P_1 \rightarrow 1^3S_0 + \gamma] = 4\alpha e^2_Q \omega^3 |\langle 1^3S_0|r|1^1P_1\rangle|^2$$ (8)

giving $\Gamma[h_b(1P) \rightarrow \eta_b(1S) + \gamma] = 37 \text{ keV}$ and

$$\Gamma[1^1P_1 \rightarrow ggg] = \frac{5}{2n_f} \times \Gamma[3^3P_1 \rightarrow q\bar{q}g]$$ (9)

giving $\Gamma[h_b(1P) \rightarrow ggg] = 50.8 \text{ keV}$. Combining the branching ratios in this decay chain yields

$$\Gamma[\Upsilon(3S) \rightarrow 1^1P_1 + \pi \rightarrow 1^1S_0 + \gamma\pi] = 4 \times 10^{-4}$$ (10)

which would yield 400 events per $10^6 \Upsilon(3S)$'s. Similarly one obtains

$$\Gamma[\psi(2S) \rightarrow 1^1P_1 + \pi \rightarrow 1^1S_0 + \gamma\pi] = 3.8 \times 10^{-4}$$ (11)
In both cases it appears that the $1^1P_1$ should be produced in sufficient numbers to be observed.

There is also the possibility that charmonium states can be observed in $B$ decay. This was recently highlighted by the Belle observation of the $\eta_c(2S)$ in $B \rightarrow \eta_c(2S)K \rightarrow KK_{s}\pi^{+}$. Belle had previously reported the observation of the $\chi_{c0}$, $\chi_{c2}$ and the $\chi_{c1}$ had been observed by both the BaBar and Belle collaborations. It had long been proposed that the $h_{c}$ could be seen in $B$ decays and the recent Belle result has led to a renewal of interest in this process.

3. S-WAVES BELOW 1 GEV

The subject of the S-waves below 1 GeV garners some of the most vigorous discussion in hadron spectroscopy. Thus, the discussion below reflects my impression of this subject which may not be held by all workers in this field. Despite this note of caution I believe that there is a growing consensus on the general features of S-wave scattering in this kinematic region, if not on all specific details.

The phenomenology of the $0^{++}$ sector reflects the many different components of the Fock space: conventional $q\bar{q}$ mesons, $q\bar{q}q\bar{q}$ states, glueballs, meson-meson molecules, and threshold effects. It is clearly a challenge to understand this sector. One starts by analyzing the raw data to produce phase shift plots and then one attempts to interpret these results in terms of underlying models.

Much of the information on low energy S-wave $\pi\pi$ scattering comes from measuring $\pi^- p \rightarrow \pi^+ \pi^- n$ at CERN [17] and $\pi^- p \rightarrow \pi^0 \pi^0 n$ at BNL [18]. Unfortunately the experiments provide fewer observables than are needed to unambiguously describe the partial waves. One must therefore make assumptions in the PWA. In particular the role of nucleon spin is ignored and the role of the $a_1$ exchange amplitude is generally neglected assuming the dominance of pion exchange. These assumptions result in ambiguities in the extraction of phase shifts from the PWA.

Kaminski, Lesniak, and Rybicki studied this problem constraining the allowed solutions by imposing unitarity and using the non-observation of inelastic scattering below the $f_0(980)$. They further related the $\pi^+ \pi^-$ to the $\pi^0 \pi^0$ amplitudes to obtain $\pi\pi$ phase shifts. Including these ingredients they presented what they believe to be a unique physical solution.

Furthermore, by separating the pseudoscalar from the pseudovector exchange amplitudes they obtain the cross sections shown in Fig. 1. The conclusion is that the $a_1$ contributions are significantly different from zero. This is an important point which should be kept in mind in future experiments. High statistics enables the differentiation between different t-channel exchange particles which results in different couplings to final states. It is a very useful bit of information in understanding the properties of the produced excited mesons.

![Figure 1. Moduli of the pseudoscalar (circles) and pseudovector amplitudes (squares) for the $\pi\pi$ scattering “down-flat” solution of Ref. [20].](image)

Given this information the next question is how to describe these phase shifts in terms of true resonances and from the dynamics between $K\bar{K}$, $K\pi$ and $\pi\pi$. This was discussed in contributions by Van Beveren and Rupp [21] and by Furman and Lesniak [22]. It is clear that one must look at the meson-meson scattering and extract the phase shifts not the resonance positions. To do this requires a multichannel approach which includes resonances (from constituent $q\bar{q}$ channels) and
meson-meson interactions. An interesting and important consequence is that the pole parameters are dependent on the coupling strengths.

As a concrete example of this approach I show results for the coupled channel calculation of Furman and Lesniak [22]. They constructed a coupled channel of two $a_0$ resonances decaying into the $\pi\eta$ and $K\bar{K}$ mesons using the coupled channel Lippman-Schwinger equation:

\begin{equation}
\langle p|T|q\rangle = \langle p|V|q\rangle + \int \frac{d^3s}{(2\pi)^3} \langle p|V|s\rangle \langle s|G|s\rangle \langle s|T|q\rangle
\end{equation}

where $T$, $V$, and $G$ are $2 \times 2$ matrices with $G$ the matrix of propagators. The resulting Argand diagrams are shown in Fig. 2. These plots show significantly different widths in the two channels which agrees with E852 and Crystal Barrel observations. The $I = 0$ sector was also studied in this approach.

![Argand diagrams for $\pi\eta$ and $K\bar{K}$ elastic scattering amplitudes. Numbers denote effective mass in units of GeV. From Ref. [22].](image)

What these multichannel approaches by Van Beveren and Rupp [21] and by Furman and Lesniak [22] and by others show is that one can obtain a good description of the low S-wave spectrum in this approach. My impression is that workers in this field have come to a consensus on the general description of S-wave scattering although there continues to be considerable debate on the details and interpretation of what these results mean.

4. EXOTIC HYBRID MESONS

The most important qualitative question in “soft QCD” is if and how glue manifests itself in the hadron spectrum. Lattice QCD and hadron models predict glueballs, objects with no constituent quark content, and hybrids, hadrons with quark content and an explicit gluon degree of freedom. It is expected that the most definitive evidence for a non $q\bar{q}$ state is to discover a state with $J^{PC}$ quantum numbers inconsistent with the quark model, so called exotics. Because the lowest lying exotic glueballs are quite massive this directs the search to exotic hybrid mesons.

The emerging picture of hybrid mesons is that of transverse excitations of the flux tube. For the light quarks this leads to the lowest mass hybrids of mass $\sim 1.9$ GeV with doubly degenerate quantum numbers. In particular, states are predicted with $J^{PC} = 0^+ −, 1^− +$, and $2^+ −$ which are inconsistent with the quark model and would therefore provide the smoking gun for new hadronic physics. There have been a number of sightings of such states [4]. For example the Brookhaven E852 experiment has seen evidence for the $\rho(1^{−+})$ exotic in the reaction $\pi^- p \to \pi^+ \pi^- \pi^− p$ [19].

Here I briefly mention an ambitious proposal to search for and map out exotic gluonic excitations at the Jefferson Laboratory in Virginia. The proposal takes advantage of the fact that exotic hybrid mesons have their quark spins aligned in an $S = 1$ state. In standard hadroproduction the incoming beam consists of $\pi$ mesons whose quark spins are in an $S = 0$ state. Since exotic hybrids have quark spins in an $S = 1$ state it is believed that hadroproduction of exotic hybrids is suppressed. In contrast, via vector meson dominance, a photon beam consists of quarks in an $S = 1$ state so it is believed that exotic hybrids are more readily produced in diffractive photoproduction by “plucking” the gluon flux tube. To this end there is a proposal to upgrade CE-BAF to 12 GeV and produce photons via coherent bremsstrahlung with a spectrum that peaks at 9 GeV. This project would add considerably to our knowledge of hybrid mesons and our understanding of confinement.
5. SUMMARY

Over the last while, there have been significant developments in heavy quarkonium physics. We expect this progress to continue with a high likelihood that the CESR collaboration should find evidence for the $2^1S_0$, $1^3P_1$ $b\bar{b}$ states. It is also possible that they will find evidence for the $3^3S_0$, $1^3D_1$ and $1^3D_3$ states. At the same time we expect that in the near future the various B-factories will discover some of the missing charmonium states in B-decay. Beyond this, the CLEO-c/CESR-c project would provide an additional avenue to study the charmonium system. Taken together, this would represent the largest advances in heavy quarkonium spectroscopy in two decades. These results would provide an important benchmark against which to measure the results of lattice QCD and the various models in the literature.

The situation with S-wave scattering at low energies is converging to a consensus on the overall details. Good agreement between theory and experiment is achieved by describing low energy scattering in the framework of a multichannel quark model. Nevertheless, there is still vigorous debate about the details and the interpretation.

Finally, we mention hybrid meson production as an important tool in understanding QCD in the low $Q^2$ regime and the nature of confinement. In the near future we look forward to results from, for example, the COMPASS experiment at CERN and photoproduction results at HERA. In the longer term we expect that the GlueX experiment at Jefferson Lab will provide a major leap forward in our understanding of gluon dynamics in the regime of Soft QCD.

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