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Some recent results on Meson Spectroscopy

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S. U. Chung

D.P.N.C., University of Geneva, Geneva, Switzerland

Physics Dept., Brookhaven National Laboratory,Upton, NY, USA *

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Abstract:

A comparative survey of established meson states with the predictions of a $q\bar{q}$ (quarkonium) model by Godfrey and Isgur shows that most meson states are well described, from pion to $\Upsilon(6S)$. However, a number of states in the light−quark isoscalar sector are not predicted at all in their model, pointing to a need for glueballs, hybrids and multi−quark states to fully account for recently reported meson states.

1. Introduction

It is well known that nonrelativistic QCD potential models give excellent description of all known heavy−quark states[1],[2]. S. Godfrey and N. Isgur[3] have produced in 1985 a relativized quarkonium model with QCD in which all known mesons, from pions to upsilons, are described in a unified framework(the GI model). Their predicted mass spectra not only fit most known meson states but also the decay modes involving hadrons and photons. The GI model reproduces to 25−MeV accuracy most well− established mesons containing light quarks and to 10−MeV accuracy all heavy−quark systems.

It may be that certain aspects of meson spectroscopy are better described in other models[4],[5],[6] but no existing phenomenological model comes close to giving a global description as that

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of Godfrey and Isgur. Indeed, the MIT bag model has been quite successful in describing light quarks and gluons confined inside a bag boundary[7]. The bag model has not been as useful, however, for hadrons containing heavy quarks or for radial excitations.

There are a number of recent reviews of meson spectroscopy with emphasis somewhat different from that of the present one. The reader is referred to Refs. [8], [9], [10], [11],[12] and [13].

A note on the notations adopted here is in order. The symbol n (for nonstrangeness) is used as a generic term to stand for u and/or d. A new set of notations has been adopted for mesons since publication of the Review of Particle Properties[14] by the Particle Data Group(PDG) in April 1986. Their new notations are followed wherever possible along with the old, familiar notations in brackets. However, certain particles with uncertain status or properties are given their old notations, e.g. E(1420), $\theta(1720)$ or $\xi(2230)$.

Due to space limitations, not all of the recent results will be discussed. This writeup is therefore limited to treating only 0^{-+} and 1^{++} states. The reader is referred to an extended version of this review which is to come out shortly as a BNL preprint and which will later be published elsewhere.

2. $J^{PC} = 1^{++}$ Isoscalar Mesons

The ground-state nonet for this J^{PC} consists of the isovector $a_1[A_1(1270)]$, the isodoublet Q_A which is a linear superposition of the $K_1[Q_1(1280)]$ and $K_1[Q_2(1400)]$, and an isoscalar $f_1[D(1285)]$. It is the second isoscalar member of this nonet that has been controversial for some time, and the problem is generally referred to as the $E(1420)/\iota(1460)$ puzzle.

According to the GI model, the 1^{++} isoscalars should occur at 1.24 GeV for $n\bar{n}$ and 1.48 GeV for $s\bar{s}$. The D(1285) with a (49 ± 6)% branching ratio into $\eta\pi\pi$ and only (11 ± 3)% into $K\bar{K}\pi$ is an undisputed $n\bar{n}$ isoscalar expected at 1.24 GeV. For its $s\bar{s}$ partner at 1.48 GeV, two choices were available; the E(1420) whose existence was never in doubt but with contradictory spin-parity assignments between 1^{++} and 0^{-+}, and the D′(1530) which was until recently seen in only one experiment[15].

A set of new results from the LASS experiment has recently been presented[16]. The collaborators have performed a partial-wave analysis of the $K\bar{K}\pi$ system in the reaction $K^-p \rightarrow K\bar{K}\pi\Lambda$ at 11 GeV/c. They confirm the existence of the 1^{++} D′(1530) and in addition see evidence of a 1^{+-} H′(1400) (see Figs. 1 and 2). Since the D′(1530) has only been seen in K^-p and not in π^-p interactions, it is the natural candidate for the 1^{++} $s\bar{s}$ state at 1.48 GeV. The H′(1400), if confirmed, should fill the role of the $s\bar{s}$ state of the nonet to which the b_1[B(1235)] and h_1[H(1190)] belong.

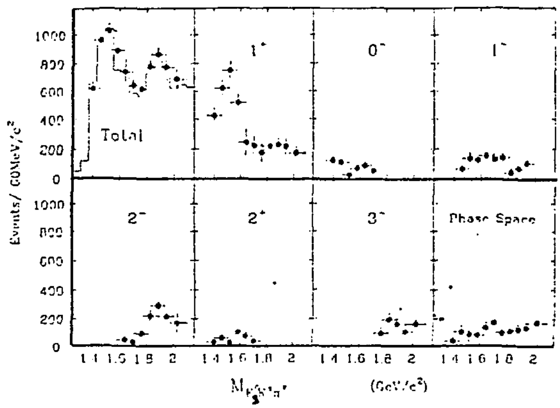

Fig. 1. The $K\bar{K}\pi$ mass spectrum and partial-waves from the LASS data[16].

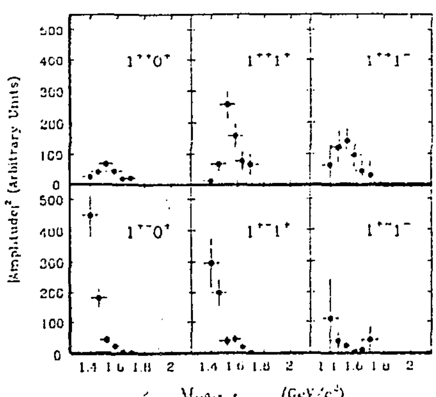

Fig. 2. Decomposition of the $J^P = 1^+$ wave into G = +1 and −1 waves for the LASS data[16].

It is noteworthy that the LASS experiment does not see the 1^{++} or the 0^{-+} E(1420) in the $K\bar{K}\pi$ system. This shows that the E(1420) has little, if any, $s\bar{s}$ component. Whatever its $q\bar{q}$ content, it is now evident that there are two spin−parity states in the E(1420) region. For the purpose of ease of reference, the 1^{++} state will be referred to simply as the E(1420), while the 0^{-+} state seen in hadroproductions will be denoted as the $\sigma(1420)$ in this review and discussed in the next section.

The best evidence that the E(1420) has spin−1 comes from two PEP experiments, Mark II[17],[9] and TPC/$\gamma\gamma$[18],[9]. The mass and width as determined by TPC/$\gamma\gamma$ are (1.417 ± 0.013) and (0.035 + 0.047/ − 0.020) GeV, consistent with the PDG values of the E. Thus the $K\bar{K}\pi$ spectra with tagged electrons show the E, whereas the untagged data do not show the E at all(not shown). The implications are that the process $\gamma\gamma^* \to K\bar{K}\pi$ results in the E formation, while the related process $\gamma\gamma \to K\bar{K}\pi$ does not; the only way to explain this is that the E has spin−1, i.e. $J^{PC} = 1^{++}$ or 1^{-+}. Indeed, Chanowitz[19] suggested that the observed resonance might in fact be an exotic 1^{-+} state. However, a preliminary spin−parity analysis prefers a 1^{++} state[20].

The Mark III data on J/ψ hadronic decays provide additional information on the E. The $K\bar{K}\pi$ system recoiling off the ω shows the E bump with mass (1442 ± 5 + 10/ − 17) MeV and width (40 + 17/ − 13 ± 5) MeV, and its spin−parity is consistent with 1^{+}[21]. The $K\bar{K}\pi$ system produced off the ϕ, on the other hand, shows no evidence of the E bump but a small enhancement at the D(1285) mass. These observations suggest that the E has little $s\bar{s}$ component, consistent with the LASS results, and that the D is not a pure $n\bar{n}$ state.

Further information on the E comes from the data of the WA76 group at the CERN Ω Spectrometer. They have studied a central production of the $K\bar{K}\pi$ system in the reaction $(\pi^+/p)p \to (\pi^+/p)(K\bar{K}\pi)p$ at 85 GeV/c[22]. From a Dalitz−plot analysis of both the D and the E regions, they conclude that the D is a 100% $1^{++}(\delta\pi)$ state and that the E bump consists of 86% $1^{++}(K^*\bar{K})$ and 14% $0^{-+}(K^*\bar{K})$. They have also studied the $\eta\pi\pi$ system in the same production mechanism[23]. They find again a $1^{++}(\delta\pi)$ but no 0^{-+} state; they quote a branching ratio $B(E \to \eta\pi\pi)/B(E \to K\bar{K}\pi) = (6 \pm 4)\%$.

New results on a radiative decay of the D(1285) have recently been presented[24]. The data come from the Lepton − F Spectrometer experiment at Serpukhov, on the reaction $\pi^- p \rightarrow Dn$ at 32.5 GeV/c with the decay $D \rightarrow \phi\gamma$. From their data on the D decay into $K\bar{K}\pi$, they derive the following branching ratio and the partial width: $B(D \rightarrow \phi\gamma) = (0.9 \pm 0.2 \pm 0.4)10^{-3}$ and $\Gamma(D \rightarrow \phi\gamma) = (23 \pm 5 \pm 10)$ KeV. The distribution in the ϕ helicity angle shows that the spin − parity is 1^{++}. The $\phi\gamma$ decay mode is an excellent probe of the $s\bar{s}$ content of the parent particle. Its observation in the D decay reveals that the D has some $s\bar{s}$ content, and this is consistent with the Mark III observation of the decay $J/\psi \rightarrow \phi D$. It is remarkable that the E signal is absent. This shows that the E does not belong to the same SU(3) nonet as the D; otherwise, the E with its higher mass(more $s\bar{s}$ content) should be seen more strongly in the $\phi\gamma$ decay.

In any case, it appears very likely that a 1^{++} E state will survive in view of the $\gamma\gamma^*$ results. Thus, the familiar quandary of an extra redundant state seems to occur in the 1^{++} sector as well. The D(1285) and D′(1530) seem to fill up the isoscalar sector; then, what is the E(1420) ? If massless nature of gluons are preserved in a two − gluon bound system, then spin − 1 is forbidden. Since the E mass is relatively low, it is not likely to be a three − gluon bound state. One may thus speculate that the E is a multiquark state. High quark charges of a multiguark system can easily accommodate the relatively abundant E production in the $\gamma\gamma^*$ channel. This may also account for its unusual production channels, namely $\gamma\gamma^*$, hadronic J/ψ decays and central production at SPS energies. Indeed, Caldwell has advanced a similar explanation regarding the E/ι puzzle[25]. One could further argue that such an unusual multiquark state is not likely to be produced in conventional peripheral productions at lower energies such as those of $K^- p$ LASS data[16] or $\pi^- p$ BNL data (see next section).

3. $J^{PC} = 0^{-+}$ Isoscalar Mesons

This sector contains the well − known η and η' as the ground − state isoscalars, mixed approximately as SU(3) octet and singlet states. The P2 scheme of the GI model allows for the first radial excitations to be nearly ideally mixed with the $n\bar{n}$ state at 1.27 GeV (imposed) and the $s\bar{s}$ state at 1.55 GeV.

Experimentally, there exist three 0^{-+} states above η and η'. They are the $\eta[\sigma(1420)]$(given the name σ in this review for convenience), seen in hadronic π^-p and $\bar{p}p$ interactions, the $\eta[\zeta(1275)]$ and the $\eta[\iota(1460)]$. Neither the $\sigma(1420)$ nor the $\iota(1460)$ is shown to be rich in $s\bar{s}$ content, and both have masses far below the predicted 1.55 GeV.

The name $\iota(1460)$ generally refers to the broad $K\bar{K}\pi$ enhancement seen in the J/ψ radiative decays[26],[9]. It is possible that a portion of the $\iota(1460)$ is in fact the $\sigma(1420)$, depending on whether the $\iota(1460)$ is to be identified as a pure or mixed gluonic state. Nevertheless, the entire enhancement from 1.30 to 1.58 GeV has been established as a 0^{-+} state using as analyzer the normal to the decay plane of the $K\bar{K}\pi$ system[27]. Thus this conclusion is independent of the nature of the intermediate states, e.g. δ or K^*, the amounts of which are poorly known at the moment for the $\iota(1460)$[28].

In this review, the state seen recoiling off ω in the J/ψ hadronic decay is assumed to be a 1^{++} state, and therefore distinct from the $\iota(1460)$. It should be borne in mind, however, that the spin-parity analysis is not yet convincing and that it is possible, though not likely, that both the radiative and hadronic J/ψ decays produce in part a same J^{PC} state in the ι region.

The $\sigma(1420)$ is produced in a variety of hadronic reactions. It was first observed in the $\bar{p}p$ annihilations at rest in the reaction $\bar{p}p \rightarrow \sigma\pi\pi$ and $\sigma \rightarrow K\bar{K}\pi$[29]. The J^{PC} is measured to be 0^{-+} and it seen to decay euqally into $\delta\pi$ and $K^*\bar{K}$. The σ is also seen as a $0^{-+}(\delta\pi)$ state in an inclusive reaction with $\bar{p}p$ annihilations at 6.6 GeV/c (an AGS771 experiment with the BNL MPS)[30].

A. Ando et al.[31] at KEK carried out an experiment to study resonance production in π^-p interactions at 8.06 GeV/c. They have performed a full partial-wave analysis of the $\eta\pi^+\pi^-$ system in the reaction $\pi^-p \rightarrow \eta\pi^+\pi^-n$. They find from this analysis the state 0^{-+} $\zeta(1275)$ and in addition observes the $\sigma(1420)$ as a $0^{-+}(\delta\pi)$ state. The masses and widths are (1279 ± 5) and (32 ± 10) MeV for the ζ, and (1420 ± 5) and (31 ± 7) MeV for the σ, respectively. Lack of a significant bump in the $\eta\pi\pi$ mass spectrum at 1.42 GeV is attributed to a destructive interference between the $0^{-+}(\delta\pi)$ wave and a $0^{-+}(\epsilon\eta)$ wave. Such an interference effect was previously hypothesized to explain absence of the $\iota(1460)$ in the $\eta\pi\pi$ channel in J/ψ radiative decays[32]. All three $\delta\pi$ states, $\zeta(1275)$, $\sigma(1420)$ and D(1285), are seen to exhibit rapid phase motions characteristic of resonant states. The 0^{-+} $\zeta(1275)$, first observed by Stanton et al.[33], is thus confirmed by Ando et al.

A high−statistics study of the E/ι phenomenon in hadronic sector is being carried out by the AGS771 experiment with the BNL MPS. The study involves the channel $K_SK^+\pi^-$ produced in π^-p, K^-p and $\bar{p}p$ interactions at 6.6 and 8.0 GeV/c. A Dalitz−plot analysis of the $K\bar{K}\pi$ system from the reaction $\pi^-p \to K_SK^+\pi^-n$ at 8 GeV/c has earlier been published, based on a portion of the data[34]. Since then, a full partial−wave analysis has been performed on the same channel with a computer program written expressly for this experiment at BNL, and the results have been presented at a number of international conferences[35]. Coincidentally, the same reaction at the same energy is being investigated by Ando et al.(performed at KEK) and has been studied earlier by Stanton et al.(performed at Argonne).

The most recent data from the AGS771 experiment[36], with a sample of some 36,000 events on the reaction $\pi^-p \to K_SK^+\pi^-n$ at 8 GeV/c, show two prominent peaks in the D and E/ι regions and, for the first time, a significant peak at around 1.52 GeV(see Fig. 3). The $K\bar{K}\pi$ spectrum has been fitted with S−wave Breit−Wigner forms over a smooth polynomial background. The fitted masses and widths for the three peaks are: 2900 events for the first peak with (1285 ± 1) and (22 ± 2) MeV, 6500 events for the second peak with (1421 ± 1) and (73 ± 6) MeV and 630 events for the third peak with (1512 ± 10) and (40 + 22) MeV.

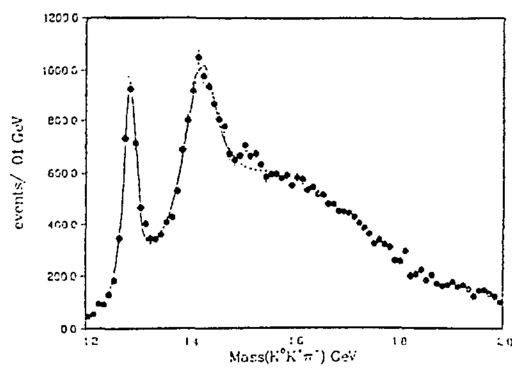

Fig. 3. The $K_SK^+\pi^-$ mass spectrum from the BNL data[36]. The solid curve is a fit with three resonances and a cubic background; the dotted curve with two resonances.

The results of a partial−wave analysis show a clear 0^{-+} signal near 1.4 GeV in both the $\delta\pi$ and $K^*\bar{K}$ decay modes(see Fig. 4). The $0^{-+}\sigma(1420)(\delta\pi)$ in addition exhibits a proper phase motion characteristic of a resonant behavior. Furthermore, a significant $0^{-+}\zeta(1275)$ is seen at around 1280 MeV. This constitutes an independent confirmation of the ζ in an independent channel $K\bar{K}\pi$. A hint of the $1^{++}D'(1530)$ is also detected for $-t < 0.2\ (GeV/c)^2$ with a phase motion consistent with that of a resonance. It is becoming increasingly clear that the presence of a $1^{+-}H'(1400)$ in this data cannot be neglected. The D′ and the H′ are much less significant, however, in the present BNL data than in the LASS data; one may conclude therefore that these are mainly $s\bar{s}$ states but contain nevertheless some $n\bar{n}$ components.

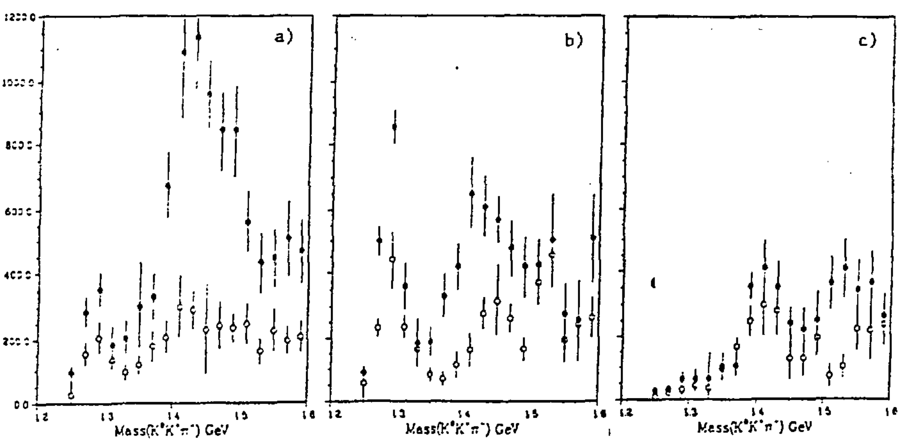

Fig. 4. Results of a partial−wave analysis for the BNL data[36] Intensities for (a) 0^{-+}, (b) 1^{++} and (c) 1^{+-} for $-t < 0.2\ GeV^2$(open circles) and for $0.2 < -t < 1.0\ GeV^2$(solid dots).

While the $\sigma(1420)$ is a significant component of the E/ι region in π^-p interactions, it is not seen in the K^-p LASS data. Therefore, the σ should be mostly an $n\bar{n}$ state. Then, where is the $s\bar{s}$ state predicted at 1.55 GeV in the P2 scheme of the GI model ? The results of the LASS analysis show no

0^{-+} state up to 2.0 GeV(see Fig. 1). The situation is likely to remain confusing until a 0^{-+} state with significant $s\bar{s}$ component is discovered experimentally, and, one may surmise, its mass is likely to be much higher than 1.5 GeV or its width very broad. At the moment no existing phenomenological models can account for the 0^{-+} sector above 1.4 GeV. It is safe to assume, in any event, that the glueball degree of freedom needs to be introduced into the model[37]. It may require in addition some or all aspects of many of the theoretical ideas in literature[5],[38],[39],[40],[41]. It may even be that presence of a hybrid meson($q\bar{q}+g$)[42],[43],[44] may be required instead of, or in addition to, a glueball and and the radial excitations.

4. Discussions and Conclusions

A survey of established meson states, with the work of Godfrey and Isgur as reference, shows the basic validity of the relativized quarkonium model. The survey highlights a need to go beyond the $q\bar{q}$ model, to include the gluonic degrees of freedom and multiquark states in the light − quark sector. In this sense, a new frontier of meson spectroscopy is being opened up in the mass region between 1.5 and 2.5 GeV, where a vast majority of the complications seems to occur which violate predictions of the quarkonium model.

Most of the major deviations from the GI model are confined to the light − quark isoscalar sector. Among the 1^{++} states, the f_1[E(1420)] is increasingly becoming a redundant state. It is possible that it may turn out to be a multiquark state. It is noted that the recently confirmed f_1[D′(1530)] is the likely candidate for being the $s\bar{s}$ member of the ground − state 1^{++} nonet with the f_1[D(1285)] as its $n\bar{n}$ isoscalar partner.

There exist two 0^{-+} states which are not understood: the $\eta[\sigma(1420)]$ seen in hadronic productions and the $\eta[\iota(1460)]$ seen in J/ψ radiative decays. It is safe to assume that there should be a large overlap between the two states. It is even possible, however remote, that the two states are in fact two different manifestations of a same state. One may also ask: Could it be that the $\iota(1460)$ is a superposition of the $\sigma(1420)$ and a glueball with its mass around 1.5 GeV ? The $\sigma(1420)$ is itself a state difficult to place in the $q\bar{q}$ model. If the $\eta[\zeta(1275)]$ is assumed to be the first radially excited $n\bar{n}$ state, then its $s\bar{s}$ partner is expected at 1.55 GeV in the GI model. The σ is some 130 MeV below this mass and furthermore it has little $s\bar{s}$ component. And yet it decays into the $K\bar{K}\pi$ channel. Is the σ a hybrid meson ?

Finally, there are exotic mesons which necessarily imply a meson state beyond $q\bar{q}$ models. They are the $\phi\pi$ state at 1480 MeV [45], a 1^{-+} $\pi\eta$ state around 1.3 GeV[46] and the X[U(3100)] meson coupling to $\Lambda\bar{p}$+ pions[47],[48]. All these states need further independent verifications.

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