Abstract. The current situation for vector meson spectroscopy is outlined, and it is shown that the data are inconsistent with the generally accepted model for meson decay. A possible resolution in terms of exotic mesons is given. Although this resolves some of the issues, fresh theoretical questions are raised.

INTRODUCTION

It is now 15 years since it was first suggested \cite{1,2} that the $\rho'(1600)$, as it was then known, is in fact a composite structure, consisting of at least two states: the $\rho(1450)$ and $\rho(1700)$. Their existence, and that of their isoscalar counterparts, the $\omega(1420)$ and $\omega(1650)$, and of an associated hidden-strangeness state, the $\phi(1680)$, is now well established \cite{3}. So it is pertinent to ask why the light-quark vector mesons remain an important field of study. The answer is straightforward. Although there is general consensus on the existence of these states, there is considerable disparity on their masses and widths. Further what is known about the composition of their hadronic decays raises fundamental questions about the nature of these states and our understanding of the mechanism of hadronic decays.

A further complication has been highlighted in two of the talks \cite{4,5} at this meeting, with indications of an isovector vector meson at a mass of around 1200 to 1250 MeV. This revives an old controversy. Many years ago evidence was presented \cite{6} for two vector states with masses $1097 \pm 19$ MeV and $1266 \pm 35$ MeV in the reaction $\gamma p \to e^+e^-p$. The evidence for these two states was obtained from the interference between the Bethe-Heitler amplitude and the real part of the hadronic photoproduction amplitude. Additionally in $\omega\pi$ photoproduction \cite{7,8,9}, $\gamma p \to (\omega\pi)p$, the $\omega\pi$ system is dominated by a low-mass enhancement with a peak at about 1250 MeV and it seemed natural to associate this with a vector state. However it appears that this enhancement is dominated by the $J^P = 1^+$ $b_1(1235)$ meson. The evidence for this comes from the analysis \cite{8,9} of the decay angular distributions of the $\omega\pi$ system. The conclusion of \cite{8} is that the data are best described by production of the $b_1(1235)$ together with a small $J^P = 1^-$ contribution.
Additionally the production mechanism does not appear to conserve $s$-channel helicity. This latter conclusion is confirmed in the experiment of [9] which had the benefit of a linearly-polarised beam. The angular distribution of the production plane relative to the photon polarisation vector has structure which is inconsistent with $s$-channel helicity conservation. The decay angular distributions of the two experiments agree and it was also concluded by [9] that the data favour a $b_1(1235)$ interpretation over a vector-meson interpretation. Preliminary data [10] on $\omega\pi$ photoproduction at high energy indicate a cross section for the 1250 MeV enhancement which is comparable to or larger than the cross section at much lower energy [8,9], with the natural inference that it is being produced diffractively. However diffractive photoproduction of the $b_1(1235)$ is inconsistent with all we know about diffraction from other reactions. It violates the Gribov-Morrison rule [11,12] and, more seriously, at the parton level it requires both spin flip and angular-momentum flip. The photon is some combination of $^3S_1$ and $^3D_1$ $q\bar{q}$ states and the $b_1(1235)$ is $^1P_1$. To avoid conflict with diffraction phenomenology, a possible interpretation of the $\omega\pi$ photoproduction data is that it is a mix of $1^-$ and $1^+$ at the lower energies, and entirely $1^-$ at high energy, requiring a vector meson at about 1250 MeV.

Obviously the light-quark vector mesons present an exciting theoretical challenge.

Information on the vector states comes principally from $e^+e^-$ annihilation, and also $\tau$ decay for the isovector states, but there are problems with much of the data:

- inconsistencies, even in recent high-statistics data
- restricted energy ranges, e.g. Novosibirsk and CLEO
- poor statistics in some channels and missing channels
- inadequate knowledge of multiparticle final states

Fortunately this is set to change with a range of possible new facilities for $e^+e^-$ annihilation and $\tau$ decay:

- upgrade of Novosibirsk to higher energy
- the PEP-N proposal at SLAC
- the use of initial state radiation (ISR) at BABAR
- emphasis on $\tau$ and charm at CLEO

There is also the possibility of complementary data on vector meson photoproduction:

- from the upgrade of CEBAF
- from real photon radiation in proton-ion and ion-ion collisions at RHIC
- photo- and electroproduction at HERA

So the future study of vector mesons looks healthy.

**THE DATA**

The key data in determining the existence of the two isovector states were $e^+e^- \rightarrow \pi^+\pi^- \ [13]$ and $e^+e^- \rightarrow \omega\pi \ [14]$. These original data sets have subsequently been augmented by data on the corresponding charged channels in $\tau$ decay.
[15,16], to which they are related by CVC. These new data confirm the earlier conclusions. The data on $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ [17] and $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ [17,18] (excluding $\omega\pi$) and the corresponding charged channels in $\tau$ decay [16] are consistent with the two-resonance interpretation [19,20], although they do not provide such good discrimination. It was also found that the $e^+e^- \rightarrow \eta\pi^+\pi^-$ cross section [21]. Independent evidence for two $J^{P} = 1^{-}$ states is provided in a high statistics study of the $\eta\pi\pi$ system in $\pi^-p$ charge exchange [22]. Decisive evidence for both the $\rho(1450)$ and $\rho(1700)$ in their $2\pi$ and $4\pi$ decays has come from the study of $\bar{p}p$ and $\bar{p}n$ annihilation [23]. The data initially available for the study of the $\omega(1420)$ and $\omega(1600)$ were $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ (which is dominated by $\rho\pi$) and $e^+e^- \rightarrow \omega\pi^+\pi^-$ [24]. The latter cross section shows a clear peak which is apparently dominated by the $\omega(1600)$. The former cross section is more sensitive to the $\omega(1420)$. However the only channel in $e^+e^-$ annihilation and $\tau$ decay with really consistent data sets over a wide energy range is the $\pi\pi$ channel, and that runs out of statistics at the upper end of the relevant energy range.

In addition to the direct experimental problems there are theoretical uncertainties which affect the analysis of $e^+e^-$ annihilation and $\tau$ decay, and which present data are insufficiently precise to resolve. Firstly there is the “tail-of-the-$\rho$” problem. In some channels, most notably $\pi\pi$ and $\pi\omega$, there is strong interference between the high-energy tail of the $\rho$ and the higher-mass resonances. The magnitude and shape of this tail are not known with any precision. They can only be specified in models and strictly should be part of the parametrisation. Different models yield different results for the masses and widths of the resonances. A related problem is the question of the relative phases. These can be specified in simple models, but we know that these models are not precise and leaving the phases as free parameters has a major effect on the results of any analysis.

The experimental challenge is easily stated; high-statistics excitation curves for a wide range of hadronic final states:

$$\pi\pi \quad \omega\pi \quad a_1\pi \quad h_1\pi \quad \rho\rho \quad \rho(\pi\pi)_{S} \quad K\bar{K} \quad K^{*}\bar{K} \cdots$$

Note that the $n\bar{n}$ states can decay to $K\bar{K}$, $K^{*}\bar{K}$ etc. with significant partial widths, so isospin separation is necessary in these channels, and there can be mixing between the isoscalar $n\bar{n}$ states and the $s\bar{s}$ states.

**THE THEORETICAL PROBLEM**

Despite these various difficulties, an apparently natural explanation for the higher-mass vector states is that they are the first radial, $2^3S_1$, and first orbital, $1^3D_1$, excitations of the $\rho$ and $\omega$ and the first radial excitation of the $\phi$, as the generally-accepted masses [3] are close to those predicted by the quark model [25]. However this argument is suspect as the masses of the corresponding $J^{P} = 1^{-}$
strange mesons are less than the predictions, particularly for the $2^3S_1$ at 1414 ± 15 MeV [3] compared to the predicted 1580 MeV [25]. Quite apart from comparing predicted and observed masses, one would expect the $n\bar{n}$ mesons to be 100 to 150 MeV lighter than their strange counterparts, putting the $2^3S_1$ at less than 1300 MeV and the $1^3D_1$ below 1600 MeV. Also this interpretation faces a more fundamental problem. The data on the $4\pi$ channels in $e^+e^-$ annihilation are not compatible with the $^3P_0$ model [26,27,28,29] which is accepted as the most successful model of meson decay. The model works well for decays of established ground-state mesons:

- widths predicted to be large, are found to be so
- widths predicted to be small, are found to be so
- calculated widths agree with data to 25 – 40%
- signs of amplitudes are correctly predicted

As far as one can ascertain the $^3P_0$ model is reliable, but it has not been seriously tested for the decays of excited states.

The $^3P_0$ model predicts that the decay of the isovector $2^3S_1$ to $4\pi$ is extremely small:

$$\Gamma_{2S\rightarrow a_1\pi} \sim 3\text{MeV} \quad \Gamma_{2S\rightarrow h_1\pi} \sim 1\text{MeV}$$

(2)

and for the isovector $1^3D_1$ the $a_1\pi$ and $h_1\pi$ decays are large and equal:

$$\Gamma_{1D\rightarrow a_1\pi} \sim \Gamma_{1D\rightarrow h_1\pi} \sim 105\text{MeV}$$

(3)

As $h_1\pi$ contributes only to the $\pi^+\pi^-\pi^0\pi^0$ channel in $e^+e^-$ annihilation, and $a_1\pi$ contributes to both $\pi^+\pi^-\pi^0\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$, then after subtraction of the $\omega\pi$ cross section from the total $\pi^+\pi^-\pi^0\pi^0$ the $^3P_0$ model predicts:

$$\sigma(e^+e^\rightarrow \pi^+\pi^-\pi^0\pi^0) > \sigma(e^+e^\rightarrow \pi^+\pi^-\pi^0\pi^0)$$

(4)

This contradicts observation over most of the available energy range. Further, and more seriously, it has been shown recently by the CMD collaboration at Novosibirsk [30] and by CLEO [31] that the dominant channel by far in $4\pi$ (excluding $\omega\pi$) up to $\sim 1.6$ GeV is $a_1\pi$. This is quite inexplicable in terms of the $^3P_0$ model. So the standard picture is wrong for the isovectors, and there are serious inconsistencies in the isoscalar channels as well. One possibility is that the $^3P_0$ model is simply failing when applied to excited states, which is an intriguing question in itself. An alternative is that there is new physics involved.

**POSSIBLE SOLUTIONS**

A favoured hypothesis is to include vector hybrids [32,33], that is $q\bar{q}g$ states. The reason for this is that, firstly, hybrid states occur naturally in QCD, and secondly, that in the relevant mass range the dominant hadronic decay of the isovector vector hybrid $\rho_H$ is believed to be $a_1\pi$ [33].
hybrids have been obtained in lattice-QCD calculations [34,35,36,37], although with quite large errors. Results from lattice QCD and other approaches, such as the bag model [38,39], flux-tube models [40], constituent gluon models [41] and QCD sum rules [42,43], show considerable variation from each other. So the absolute mass scale is somewhat imprecise, predictions for the lightest hybrid lying between 1.3 and 1.9 GeV. However it does seem generally agreed that the mass ordering is $0^{-+} < 1^{-+} < 1^{--} < 2^{-+}$.

Evidence for the excitation of gluonic degrees of freedom has emerged in several processes. Two experiments [44,45] have evidence for an exotic $J^{PC} = 1^{-+}$ resonance, $\hat{\rho}(1600)$ in the $\rho^0 \pi^-$ channel in the reaction $\pi^- N \to (\pi^+ \pi^- \pi^-) N$. A peak in the $\eta\pi$ mass spectrum at $\sim 1400$ MeV with $J^{PC} = 1^{-+}$ in $\pi^- N \to (\eta\pi^-) N$ has also been interpreted as a resonance [46]. Supporting evidence for the 1400 state in the same mode comes from $\bar{p} p \to \eta\pi^- \pi^+$ [47]. There is evidence [48] for two isovector $0^{-+}$ states in the mass region 1.4 to 1.9 GeV; $\pi(1600)$ and $\pi(1800)$. The quark model predicts only one. Taking the mass of the $1^{-+} \sim 1.4$ GeV, then the $0^{-+}$ is at $\sim 1.3$ GeV and the lightest $1^{--}$ at $\sim 1.65$ GeV, which is in the range required for the mixing hypothesis to work. Of course if hybrids are comparatively heavy, that is the $\hat{\rho}(1600)$ is the lightest $1^{-+}$ state, and the $\pi(1600)$ presumably the corresponding $0^{-+}$ hybrid (or at least with a significant hybrid component) then the vector hybrid mass $\sim 2.0$ GeV making strong mixing with the radial and orbital excitations unlikely.

Two specific models for the hadronic hybrids are the flux-tube model [33,40] and the constituent gluon model [49,50]. There are some substantial differences in their predictions for hybrid decays. For the isovector $1^{--}$ the flux-tube model predicts $a_1\pi$ as essentially the only hadronic mode, and a width of $\sim 100$ MeV. The constituent gluon model predicts dominant $a_1\pi$, but with significant $\rho(\pi\pi)_S$ and $\omega\pi$ components, and a larger width. For the isoscalar $1^{--}$ the flux-tube model predicts $\rho\pi$ as essentially the only hadronic mode, with a width of $\sim 20$ MeV. The constituent gluon model predicts dominant $\rho\pi$, a significant $\omega(\pi\pi)_S$ component and a larger width.

An alternative explanation could be to invoke the old concept of multiquark states. These are defined as solutions of the multiquark Hamiltonian with totally confined boundary conditions. In the pioneering paper on bag-model four-quarks [51], the states were considered with all interquark orbital momenta equal to zero. Such states easily decay into mesons, so that these multiquarks usually do not exist as relatively narrow resonances. The $q^2\bar{q}^2$ states with vector quantum numbers necessarily contain an extra unit of orbital momentum between constituents, which could reduce the amplitude of their "superallowed" decays. Namely, for the four-quark configurations corresponding to the $(3\bar{3})$ diquark-antidiquark colour representation, $J^{PC} = 1^{--}$ quantum numbers are achieved if orbital excitation $L = 1$ is taken between the diquark and the antidiquark. Extra suppresion of superallowed decay happens if the string model for the multiquark state is adopted, in which a string with junction and antijunction points is formed between the diquark
and the antiquark.

In the bag model the masses of such vector states [52] lie well above 1.7 GeV. The string model with junctions [53] lowers the mass to 1.5 GeV giving the possibility for $q^2\bar{q}^2$ states to participate in the higher vector meson phenomena. The detailed structure of $q^2\bar{q}^2$ vector states was considered in [54]. The peculiar feature of the multiquark scenario is that it is necessary to take into account three lowest states with different total quark spins. Another interesting feature is that the lowest isovector state is about 200 MeV higher than the lowest isoscalar one. Similarly to the hybrid case, selection rules for the multiquark superallowed decay exist which forbid the decay into a pair of $S$-wave mesons [54]. The main decay modes of $q^2\bar{q}^2$ states are to $S$-wave plus $P$-wave mesons, and, in principle, mixing between $qq\bar{q}$ and $q^2\bar{q}^2$ states does the same job as mixing between $qq$ states and hybrids. The resulting mixing scheme should include five states, and is much more complicated than in the hybrid case. On the other hand it offers new opportunities, as the low-lying four-quark $\rho(1250)$ and $\omega(1100)$ might be responsible for the photoproduction data and the former be the “new” vector meson at about 1250 MeV.

The general conclusion is that the $e^+e^-\,\text{annihilation}$ and $\tau$-decay data require the existence of a “hidden” vector exotics in the isovector and isoscalar channels (assuming that the $^3P_0$ results are qualitatively reliable). The mixing required is non-trivial, although schemes can be devised which are qualitatively compatible with the data [54,55]. The unseen physical states are “off-stage”, in the 1.9 to 2.1 GeV mass region. Nonetheless, it appears difficult to achieve quantitative agreement with data (within the constraint of specific models) unless the exotics and the $^1D_1$ states have direct electromagnetic coupling. At the simplest level hybrids do not, but these couplings can be generated by relativistic corrections at the parton level [25] or via intermediate hadronic states, for example hybrid $\rightarrow a_1\pi$ $\rightarrow \rho$ $\rightarrow e^+e^-$. 

**RADIATIVE DECAYS: AN ALTERNATIVE**

Radiative decays offer several theoretical advantages. They are a much better probe of wave functions, and hence of models, than are hadronic decay modes because of the direct coupling to the charges and spins of the constituents. This can be particularly relevant, for example, in distinguishing gluonic excitations from conventional radial and orbital excitations as in a $1^{--}$ hybrid the $qq\bar{q}$ are in a spin-singlet state which is the reverse of the usual $q\bar{q}$ configuration. The results of detailed calculation are encouraging [56]. Crucial channels can be specified and, importantly from the practical point of view, it is found that interesting channels should be easily identified. The widths for radiative decays to pseudoscalar states are generally small, but some of those to the $1P$ states are large. Some preliminary results are given in Table 1.
TABLE 1. Preliminary radiative widths in keV [56].

| State          | $Γ(ρ_S)$ | $Γ(ω_S)$ | $Γ(ρ_D)$ | $Γ(ω_D)$ |
|----------------|----------|----------|----------|----------|
| $a_0(1300)γ$   | $∼15$    | $∼140$   | $∼110$   | $∼990$   |
| $a_1(1260)γ$   | $∼45$    | $∼420$   | $∼80$    | $∼740$   |
| $a_2(1320)γ$   | $∼75$    | $∼695$   | $∼12$    | $∼110$   |
| $f_0(1300)γ$   | $∼140$   | $∼15$    | $∼990$   | $∼110$   |
| $f_1(1285)γ$   | $∼420$   | $∼45$    | $∼740$   | $∼80$    |
| $f_2(1270)γ$   | $∼695$   | $∼75$    | $∼110$   | $∼12$    |

The larger partial widths should be measurable at the new high-intensity facilities. In some cases they may be measurable in the data from present experiments. We give two specific examples of quarkonia decay and a comment on hybrid radiative decay.

The $ωη$ decay of the $ω(1650)$ has been observed in the E852 experiment [57]. If the $ω(1650)$ is the $1D q̄q$ excitation of the $ω$, then the $^3P_0$ model gives the partial width for this decay as 13 MeV [29]. The partial width for the radiative decay $ω(1650) → a_1(1250)γ$ is of the order of 1 MeV, that is about 8% of the $ωη$ width. The E852 experiment has several thousand events in the $ωη$, so we may expect several hundred events in the $a_1γ$ channel. Similarly both the $ρ(1450)$ and $ρ(1700)$ are seen by the VES collaboration [58] in the $ρη$ channel with several thousand events. Both these states have strong radiative decays, the $ρ(1450)$ to $f_2(1270)γ$ and the $ρ(1700)$ to $f_1(1285)γ$ both of the order of 1 MeV. Assuming that the $ρ(1450)$ and the $ρ(1700)$ are respectively the $2S$ and the $1D$ excitations of the $ρ$, then the $^3P_0$ model gives the partial widths for the $ρη$ decays of the $ρ(1450)$ and $ρ(1700)$ as 23 MeV and 25 MeV respectively [29], so the radiative decays should again be present at the level of a few hundred events.

The $π(1800)$ is interesting as it could be a conventional $π(2S)$ or $π(3S)$, the latter being the more natural if the $π(1300)$ is interpreted as the $π(2S)$ as in the conventional quark model, or it could be a $π_g$ hybrid. The $ω(1420)$ and $ω(1650)$ could be conventional $2S$ and $1D$ or a hybrid $ω_g$. The widths of the radiative decays $π(1800) → ω(1420)$ or $ω(1650)$ depend sensitively on which of these configurations the mesons are in, and potentially can discriminate among them. For example, if the $π(1800)$ is $2S$ then the width of the radiative decay to $ω(1420)$ will be large, 0.5 to 1.0 MeV. If it is $3S$ then the radiative decay will be strongly suppressed because of the orthogonality of the wave functions, unless the $ω(1420)$ is $3S$, which is highly unlikely. Equally, if the $π(1800)$ is a hybrid, then the width of the radiative decay to the hybrid $ω_g$ will again be large. Thus if a radiative width of $∼1$ MeV is found then the two states must be siblings, which would be most natural for hybrids.
SUMMARY

Despite 15 years of work we do not yet understand the light-quark vectors. The data raise tantalising questions which go to the heart of nonperturbative QCD:

- How many light-quark vector mesons are there?
- Are there exotic states hiding in there?
- What are the masses, widths, decay channels?
- Does the $^3P_0$ model fail?
- If there are exotics, where are the corresponding states in the strange and charm sectors?

The $e^+e^-$ partial widths and the radiative decay widths of the light-quark vector mesons provide a particularly sensitive probe of wave functions, and the nature of the states involved. The hadronic channels test our understanding of decay mechanisms for radial and orbital excitations, and for exotic states if they are present.

We are in the intriguing position of having sufficient information to realise that the light-quark vector mesons present an exciting challenge, but have insufficient information to solve it. Whatever the answers, new physics is guaranteed!

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