Light Vector Meson Spectroscopy

A. Donnachie
University of Manchester, England

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 (hybrid) mesons is given. Although this hypothesis resolves some of the issues, fresh theoretical questions are raised. It is argued that high-precision e^+e^- annihilation data provide an excellent laboratory for studying many aspects of nonperturbative QCD.

1. THE PROBLEM

It is now 15 years since it was first suggested [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 [3]. The key data in determining the existence of the two isovector states were $e^+e^- \to \pi^+\pi^-$ [4] and $e^+e^- \to \omega\pi$ [5]. These original data sets have subsequently been augmented by data on the corresponding charged channels in τ decay [6–9], to which they are related by CVC. These new data confirm the earlier conclusions. The data on $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ [10, 11] and $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ [10, 12] (excluding $\omega\pi$) and the corresponding charged channels in τ decay [7, 8] are consistent with the two-resonance interpretation [13, 14], although they do not provide such good discrimination. Itwas also found that the $e^+e^- \to \eta\pi^+\pi^-$ cross section is better fitted with two interfering resonances than with a single state [15]. Independent evidence for two $J^P = 1^-$ states is provided in a high statistics study of the $\eta\pi\pi$ system in π^-p charge exchange [16]. Decisive evidence for both the $\rho(1450)$ and $\rho(1700)$ in their 2π and 4π decays has come from the study of $\bar{p}p$ and $\bar{p}n$ annihilation [17]. The data initially available for the study of the $\omega(1420)$ and $\omega(1600)$ were $e^+e^- \to \pi^+\pi^-\pi^0$ [11, 18] (which is dominated by $\rho\pi$) and $e^+e^- \to \omega\pi^+\pi^-$ [18]. 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 $\omega(1420)$. More recent and more precise data [19] on $e^+e^- \to \pi^+\pi^-\pi^0$ below 1.4 GeV confirm [14] the $\omega(1420)$.

However, although there is general consensus on the existence of these states, there is considerable disparity on the masses and widths of these resonances. Information on the vector states comes principally from e^+e^- annihilation and τ decay, 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
- $\sum \sigma_{\text{exclusive}} > \sigma_{\text{inclusive}}$

In fact the only channel with really consistent data sets over a wide energy range is the $\pi\pi$ channel, although even that runs out of statistics at the upper end of the energy range. The comparatively low statistics of the older data, the restricted energy range of the newer data with higher statistics, and persisting inconsistencies in data from different experiments rule out precision fits.

There are also theoretical uncertainties which affect the analysis of e^+e^- annihilation and τ decay, and which present data are insufficiently precise to resolve. Firstly there is the "tail-of-the-ρ" problem. In some channels, most notably $\pi\pi$ and $\pi\omega$, there is strong interference between the high-energy tail of the ρ 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.

Thus only the qualitative features emerge, and apparent precision is in reality the result of implicit, or explicit, theoretical assumptions.

Despite these difficulties, the existence of the higher-mass states is not in doubt, and a natural explanation for them is that they are the first radial, 2^3S_1, and first orbital, 1^3D_1, excitations of the ρ and ω and the first radial excitation of the ϕ, as the generally-accepted masses [3] are close to those predicted by the quark model [20]. However this interpretation faces a fundamental problem. The data on the 4π channels in e^+e^- annihilation are not compatible with the $^3P_0$ model [21–24], 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 4π is extremely small:

$$\Gamma_{2S\to a_1\pi} \sim 3 \text{ MeV} \qquad \Gamma_{2S\to h_1\pi} \sim 1 \text{ MeV} \tag{1}$$

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

$$\Gamma_{1D\to a_1\pi} \sim \Gamma_{1D\to h_1\pi} \sim 105 \text{ MeV} \tag{2}$$

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 $\pi^+\pi^-\pi^+\pi^-$ 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:

$$\sigma(e^+e^- \to \pi^+\pi^-\pi^0\pi^0) > \sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^-) \tag{3}$$

This contradicts observation over much of the available energy range. Below $\sim$ 1.6 GeV $\sigma(\pi^+\pi^-\pi^+\pi^-) \approx 2\sigma(\pi^+\pi^-\pi^0\pi^0)$, although at higher energies $\sigma(\pi^+\pi^-\pi^0\pi^0)$ is the larger. Further, and more seriously, it has been shown recently by the CMD collaboration at Novosibirsk [25] and by CLEO [8] that the dominant channel by far in 4π (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.

2. A SOLUTION

A favoured hypothesis is to include vector hybrids [26, 27], 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 ρ_H is believed to be $a_1\pi$ [27]. The masses of light-quark hybrids have been obtained in lattice-QCD calculations [28–31], although with quite large errors. Results from lattice QCD and other approaches, such as the bag model [32, 33], flux-tube models [34], constituent gluon models [35] and QCD sum rules [36, 37], 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 [38, 39] 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 [40]. Supporting evidence for the 1400 state in the same mode comes from $\bar{p}p \to \eta\pi^-\pi^+$ [41]. There is evidence [42] 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 [27, 34] and the constituent gluon model [43, 44]. 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.

The general conclusion is that the e^+e^- annihilation and τ-decay data require the existence of a "hidden" vector hybrid 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 [45]. 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 hybrids and the 1^3D_1 states have direct electromagnetic coupling. At the simplest level they do not, but these couplings can be generated by relativistic corrections at the parton level [20] or via intermediate hadronic states, for example hybrid $\to a_1\pi \to$ "ρ" $\to e^+e^-$.

To extract the information will require excitation curves for a wide range of hadronic final states:

$$\pi\pi \quad \omega\pi \quad a_1\pi \quad h_1\pi \quad \rho\rho \quad \rho(\pi\pi)_S \quad K\bar{K} \quad K^*\bar{K} \cdots \tag{4}$$

Note that the $n\bar{n}$ states can decay to $K\bar{K}$, $K^*\bar{K}$ etc. with significant partial widths:

$$\Gamma_{2S\to K\bar{K}} \sim 30MeV \quad \Gamma_{1D\to K\bar{K}} \sim 40MeV \tag{5}$$

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.

Radiative decays allow a clean separation of the 2S and 1D states. Preliminary widths in keV are [46]:

Obviously the $f_2\gamma$ channel selects the ρ_S state uniquely. Additionally, these decays are a much more direct probe of

	$\Gamma(\rho_S)$	$\Gamma(\omega_S)$	$\Gamma(\rho_D)$	$\Gamma(\omega_D)$
$a_1\gamma$	~ 80	~ 750	~ 200	~ 1800
$a_2\gamma$	~ 100	~ 900	~ 10	~ 100
$f_1\gamma$	~ 650	~ 70	~ 1700	~ 200
$f_2\gamma$	~ 1200	~ 130	~ 120	~ 15

wave functions, and hence of models, than are hadronic decay modes.

3. SUMMARY

Despite 15 years of work we do not yet understand the light-quark vectors. Present data raise tantalising questions which go to the heart of nonperturbative QCD but are incapable of answering them. These questions include:

• How many light-quark vector mesons are there?
• What are their masses, widths, decay channels?
• Do standard models of hadronic decay fail?
• What hybrid states are hiding in there?
• What is the nature of hybrids: flux tube or constituent gluon?
• Are the masses of hybrids compatible with lattice QCD?

High-statistics, comprehensive e^+e^- annihilation data provides by far the best way to answer these and related questions. The data are a unique $J^{PC} = 1^{--}$ laboratory.

Whatever the answers, new physics is guaranteed!

REFERENCES

[1] C. Erkal and M.G. Olsson: Z.Phys. **C31** (1986) 615
[2] A. Donnachie and H. Mirzaie: Z.Phys. **C33** (1987) 407
[3] Particle Data Group: European Physical Journal C15 (2000) 1
[4] L. M. Barkov et al: Nucl.Phys. **B256** (1985) 365
D. Bisello et al: Phys.Lett. **B220** (1989) 321
[5] S. I. Dolinsky et al: Phys.Lett. **B174**, (1986) 453
[6] R. Barate et al (ALEPH Collaboration): Z.Phys. **C76** (1997) 15
[7] H. Albrecht et al (ARGUS Collaboration): Phys.Lett. **B185** (1987) 223
[8] K.W. Edwards et al (CLEO Collaboration): Phys.Rev **D61** (2000) 072003
[9] S. Anderson et al (CLEO Collaboration): Phys.Rev **D61** (2000) 112002
[10] S. I. Dolinsky et al: Phys.Rep. **202** (1991) 99
[11] L Stanco (DM2 Collaboration): Proc. Hadron'91, Maryland, 1991; ed Y. Oneda and D. Peaslee (World Scientific, Singapore, 1992) p.84
[12] C. Bacci et al: Nucl.Phys. **B184** (1981) 31
G. Cosme et al: Nucl.Phys. **B152** (1979) 215
[13] A. B. Clegg and A. Donnachie: Z.Phys. **C62** (1994) 455
A. Donnachie and A.B. Clegg: Phys.Rev. **D51** (1995) 4979
[14] N.N. Achasov and A.A. Kozhevnikov: Phys.Rev. **D55** (1997) 2663; Phys.Rev. **D62** (2000) 117503
[15] A. Antonelli et al: Phys.Lett. **B212** (1988) 133
[16] S. Fukui et al: Phys.Lett. **B202** (1988) 133
[17] A. Abele et al (Crystal Barrel Collaboration): Phys.Lett. **B391** (1997) 191
[18] A. Antonelli et al: Z.Phys. **56** (1992) 15
[19] M.N. Achasov et al (SND Collaboration): Phys.Lett. **B462** (1999) 365
[20] S. Godfrey and N. Isgur: Phys.Rev. **D32** (1985) 189
[21] G. Busetto and L. Oliver: Z.Phys. **C20** (1983) 247
P. Geiger and E.S. Swanson: Phys.Rev. **D50** (1994) 6855
H.G. Blundell and S. Godfrey: Phys.Rev. **D53** (1996) 3700
[22] R. Kokoski and N. Isgur: Phys.Rev. **D35** (1987) 907
[23] E.S. Ackleh, T. Barnes and E.S. Swanson: Phys.Rev. **D54** (1996) 6811
[24] T. Barnes, F.E. Close, P.R. Page and E.S. Swanson: Phys.Rev. **D55** (1997) 4157
[25] R.R. Akhmetshin et al (CMD Collaboration): Phys.Lett. **B466** (1999) 392
[26] A. Donnachie and Yu.S. Kalashnikova: Z.Phys. **C59** (1993) 621
[27] F.E. Close and P.R. Page: Phys.Rev. **D56** (1997) 1584
[28] P. Lacock, C. Michael, P. Boyle and P. Rowland: Phys.Lett. **B401** (1997) 308
[29] C. Bernard et al: Phys.Rev **D56** (1997) 7039; Nucl.Phys.Proc.Supp. 73 (1999) 264
[30] P. Lacock and K. Schilling: Nucl.Phys.Proc.Supp. 73 (1999) 261
[31] C. McNeile: hep-lat/9904013
[32] T. Barnes and F.E. Close: Phys.Lett. **116B** (1982) 365; *ibid* **123B** (1983) 89
T. Barnes, F.E. Close and F. de Viron: Nucl.Phys. **B224** (1983) 241
[33] M. Chanowitz and S. Sharpe: Nucl.Phys. **B222** (1983) 211
[34] N. Isgur and J.E. Paton: Phys.Lett. **124B** (1983) 247
N. Isgur, R. Kokoski and J.E. Paton: Phys.Rev.Lett. **54**, 869 (1985)
N. Isgur and J.E. Paton: Phys.Rev. **D31** (1985) 2910
T. Barnes, F.E. Close, E.S. Swanson: Phys.Rev. **D52** (1995) 5242
[35] Yu.S. Kalashnikova and Yu.B. Yufryakov: Phys. Lett. **B359** (1995) 175
Yu.S. Kalashnikova and Yu.B.Yufryakov: Phys. At. Nucl. **60** (1997) 307
[36] I.I. Balitsky, D.I. Dyakonov and A.V. Yung: Z.Phys. **C33** (1986) 265
[37] J.I. Latorre, P. Pascual and S. Narison: Z.Phys. **C34** (1987) 347
[38] D.P. Weygand (E852 Collaboration): Proc. HADRON'97, BNL; ed S-U Chung and H.J. Willutski (American Institute of Physics, New York, 1998) p.313
[39] Yu.P. Gouz (VES Collaboration): Proc. XXVI ICHEP (DALLAS, 1992),ed. J.R. Sanford, p.572
[40] D.R. Thompson et al (E852 Collaboration): Phys.Rev.Lett. **79** (1997) 1630

[41] A. Abele et al (Crystal Barrel Collaboration): Phys.Lett. **B423** (1998) 175
[42] A. Zaitsev (VES Collaboration): Proc. Hadron'97, BNL, 1997; ed S-U Chung and H.J. Willutski (American Institute of Physics, New York, (1998) p.461
D V Amelin (VES Collaboration): *ibid* p.770
[43] A. Le Yaounac, L. Oliver, O. Pène, J.C. Raynal and S. Ono: Z.Phys. **C28** (1985) 309
F. Iddir, A. Le Yaouanc, L. Oliver, O. Pène and J.C. Raynal: Phys.Lett. **B205** (1988) 564
[44] Yu.S. Kalashnikova: Z.Phys. **C62** (1994) 323
[45] A. Donnachie and Yu.S. Kalashnikova: Phys.Rev. **D60** (1999) 114011
[46] F.E. Close, A. Donnachie and Yu.S. Kalashnikova: in preparation