Vector Mesons of Light Quarks

S. Eidelman[a]

[a]Budker Institute of Nuclear Physics,
11 Lavrentyev St., 630090 Novosibirsk, Russia

A brief review of vector mesons made of light quarks is presented.

1. INTRODUCTION

Hadrons with quantum numbers $J^{PC} = 1^{--}$ can be directly produced in one-photon e^+e^- annihilation. They are observed as resonances in cross sections of exclusive processes $e^+e^- \to (2-6)h, h = \pi, K, \eta, p, \ldots$. Their properties (mass, total and leptonic width, branching fractions) provide information on interactions of light (u, d, s) quarks. Detailed studies of such particles and searches for exotic states like hybrids and glueballs allow a test of various theoretical models (Chiral perturbation theory, Vector Meson Dominance, potential models, CVC relations between e^+e^- and τ) and give input to better understanding of low energy strong interactions and thus further development of QCD. High-precision measurements of various cross sections are also important for the determination of fundamental physical quantities ($(g_\mu - 2)/2$, $\alpha(M_Z^2)$, α_s, quark and gluon condensates.

We present here a brief review of the current status of vector states in the center-of-mass (c.m.) energy range 1.0–2.5 GeV. It is mostly focused on recent experiments performed by a scan method with the CMD-2, SND and BES detectors as well as with the initial-state radiation method (ISR) extensively employed in the BaBar experiment. For a review of previous measurements in this energy range see, e.g., Ref. [1].

2. FINAL HADRONIC STATES

From experiment it is known that production of hadrons in the energy range under discussion is saturated by the final states with n pions ($n = 2-6$), and combinations of two or even four kaons with some number of pions (up to three). There is some recent evidence for production of an additional η meson in final states with pions and kaons [2].

Note that the same final state can be reached via different intermediate mechanisms involving various resonances. For example, the $\pi^+\pi^-\pi^+\pi^-$ final state can be obtained via $a_1\pi$, $f_0\rho^0$, $a_2\pi$, $\pi'\pi$, ... Correct description of such processes requires taking into account interference effects between amplitudes of different subprocesses as well as permutations of identical pions.

Until recently the available statistics in the studies of exclusive hadronic processes were limited and precluded detailed measurements of the parameters of vector mesons observed between 1 and 2 GeV. According to PDG [3], there are two ω''s ($\omega(1420)$ and $\omega(1650)$), two ρ''s ($\rho(1450)$ and $\rho(1700)$), and one ϕ' ($\phi(1680)$). However, even their basic parameters (M, Γ, Γ_{ee}) are badly known. For example, two ρ''s are observed in most of the reactions as a broad structure at ~ 1.6 GeV. The only exception is a very recent high-statistics measurement of the two-pion decay of the τ lepton in which the two-pion invariant mass distribution clearly shows three interfering ρ mesons [4], see Fig. 1.

The position of the five vector states above is in satisfactory agreement with the Godfrey-Isgur relativized quark model with QCD, which actually predicts two sets of vector states (ρ, ω, ϕ) from 1 to 2 GeV [5]. Detailed comparison with any theoretical predictions will require isospin analysis and much better accuracy. For example,

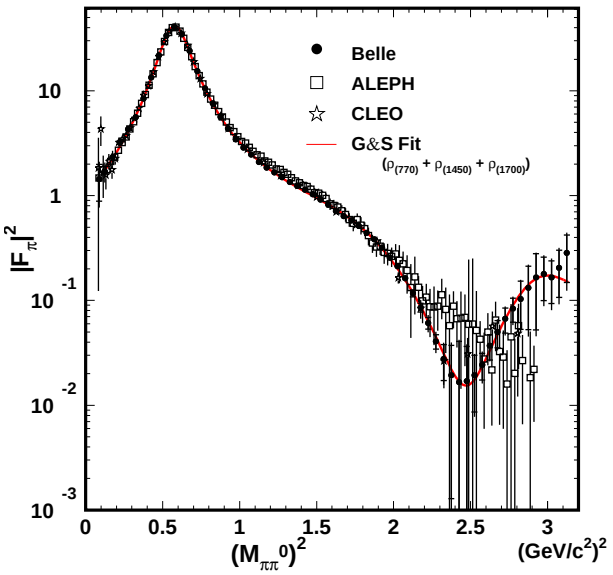

Figure 1. $M_{2\pi}$ distribution in $\tau \to \pi\pi\nu$ at Belle

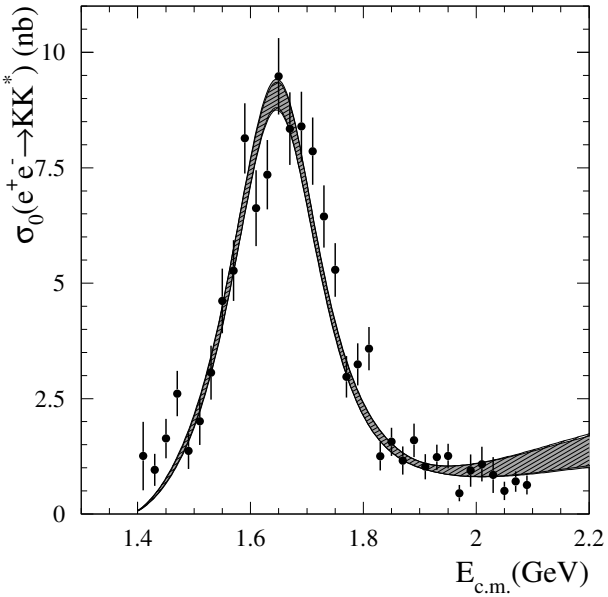

Figure 2. Isoscalar component of the cross section of K^*K production

BaBar recently studied the $K\bar{K}\pi$ final state and found that it is dominated by the K^*K mechanism [6]. Observation of two charge combinations ($K^+K^-\pi^0$ and $K^0_S K^\pm\pi^\mp$) and their Dalitz plot analysis allow to disentagle isospin-zero and isospin-one contributions, (Fig. 2 and Fig. 3).

3. ω' MESONS

Recent studies of the processes $\pi^+\pi^-\pi^0$ ($\rho\pi$) by SND [7] and BaBar [8] as well as $2\pi^+2\pi^-\pi^0$ ($\omega\pi^+\pi^-$) by CMD-2 [9] and BaBar [2] confirmed the existence of the $\omega(1420)$ and $\omega(1650)$ and significantly affected the values of their parameters. In the $\pi^+\pi^-\pi^0$ final state the cross sections measured by SND and BaBar are in good agreement at $\sqrt{s} < 1.4$ GeV whereas above this energy the BaBar cross section is more than two times larger than that previously measured by DM2 [10]. BaBar also reported observation of the $\omega\eta$ decay mode of the $\omega(1650)$ [11], but with a somewhat smaller width (114 ± 14 MeV) than in the original observation in $\pi^- p$ collisions, where a width of 250 ± 50 MeV was measured [12]. It is also worth noting that estimated values of the leptonic width for the ω' states are significantly higher than those expected in Ref. [5].

4. ρ' MESONS

$\rho(1450)$ and $\rho(1700)$ are expected to predominantly decay into four pions. Old measurements of both $2\pi^+2\pi^-$ and $\pi^+\pi^-2\pi^0$ by DM2 [13] agree with those of CMD-2 [14], SND [15] and BaBar [16], but all experiments always show one broad structure only. This can be due to peculiar interference pattern or existence of additional exotic states close to the regular $q\bar{q}$ states and mixed with them [17,18]. It is also possible that the $\rho(1450)$ and $\rho(1700)$ have different decay modes, so that there are different energy thresholds and energy dependence in each particular case.

Recently BaBar reported observation of two structures at ~ 1.5 GeV [6]. A broad one in the KK^* state (a width of $418 \pm 25 \pm 4$ MeV) can be

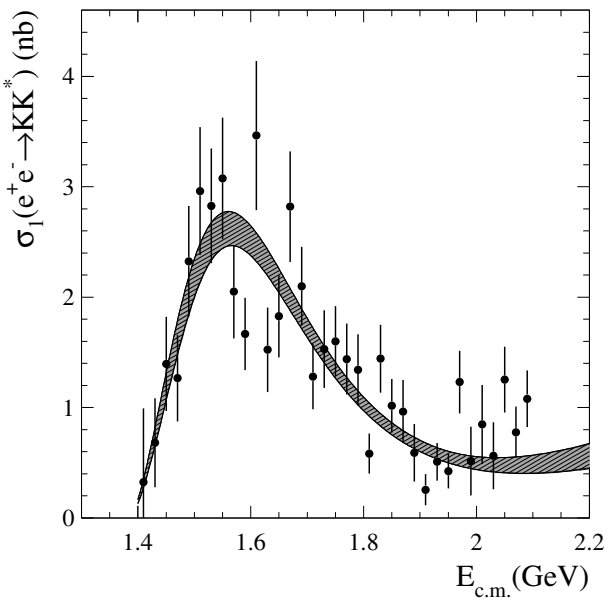

Figure 3. Isovector component of the cross section of K^*K production

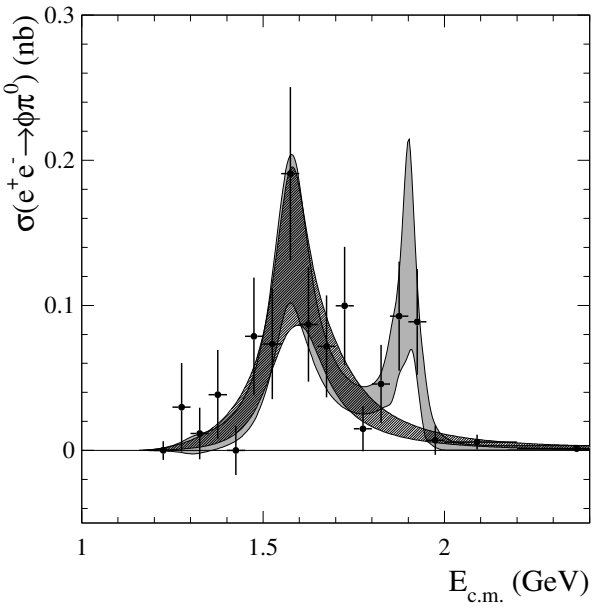

Figure 4. Cross section of the process $e^+e^- \to \phi\pi^0$

also due to the overlapping $\rho(1450)$ and $\rho(1700)$ resonances, but the one in the $\phi\pi^0$ final state has a much smaller width of $144 \pm 75 \pm 43$ MeV. Its properties are very close to those of the $C(1480)$ state observed more than 20 years ago in a single experiment using $\pi^- p$ collisions [19] (and not confirmed by searches in e^+e^- [20] and $p\bar{p}$ [21] annihilation).

The $\phi\pi^0$ cross section shown in Fig. 4 also exhibits some narrow structure at 1.9 GeV, which may be $\rho(1900)$ earlier observed in the $3\pi^+3\pi^-$ state in photoproduction [22], in the total R in e^+e^- [23] as well as in both $3\pi^+3\pi^-$ and $2\pi^+2\pi^-2\pi^0$ cross sections by DM2 [24] and BaBar [11] (although with a larger width). It should be noted that a statistical significance of these findings is not yet high and the authors themselves can't exclude that they observe an OZI-violating decay mode of the $\rho(1700)$ [11].

Based on the ISR study, BaBar also reports a measurement of the $\eta'(958)\pi^+\pi^-$ and $f_1(1285)\pi^+\pi^-$ (Fig. 5) cross sections with clear evidence for the $\rho(2150)$ meson [2].

Finally, it is worth noting that BES recently reported a very broad (~ 800 MeV) K^+K^- state at about 1.5 GeV produced in J/ψ decays [25]. Partial wave analysis gives for it isovector quantum numbers. Such a pattern of the cross section can hardly be reconciled with what was observed before in both K^+K^- and $K^0_SK^0_L$ final states.

5. ϕ' MESONS

Until recently evidence for the $\phi(1680)$ was only based on the old observation of a structure in the $K^0_SK^\pm\pi^\mp$ final state by DM1 [26]. BaBar observed it in both KK^* and $\phi\eta$ (Fig. 6) final states [6]. There is, however, a conflicting result of FOCUS [27], which observes a structure with similar parameters in the K^+K^- and does not observe it in the KK^* final state.

Finally, BaBar observes a new isoscalar resonance in the $K^+K^-\pi^+\pi^-$ and $K^+K^-\pi^0\pi^0$ final states (predominantly $\phi f_0(980)$) at 2.12 GeV [16,

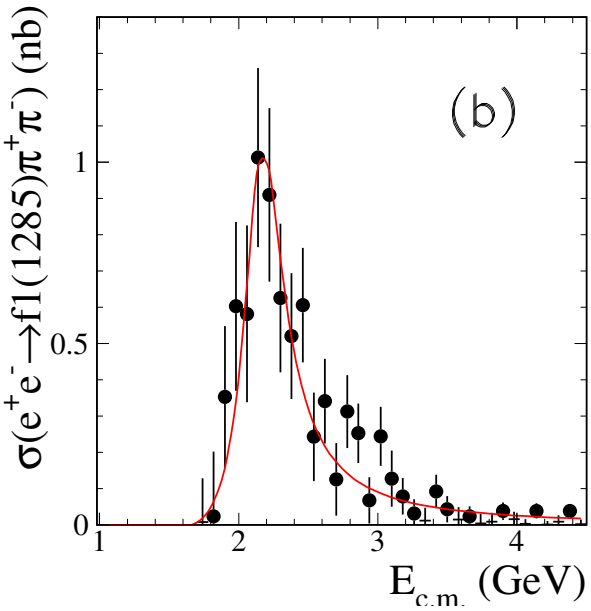

Figure 5. Cross section of the process $e^+e^- \to f_1(1285)\pi^+\pi^-$

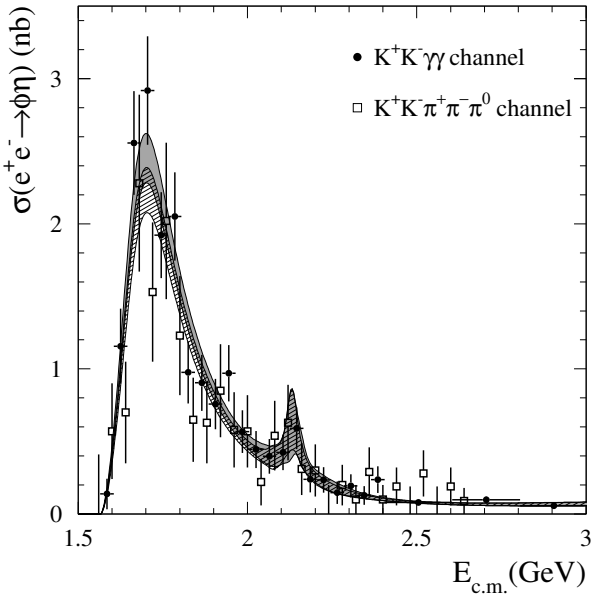

Figure 6. Cross section of the process $e^+e^- \to \phi\eta$

28], see Fig. 7. This result is confirmed by the BES Collaboration which observed the same final state in $J/\psi \to \eta\phi f_0(980)$ decay [29].

6. CONCLUSIONS

A big number of vector mesons made of light quarks have been observed above the $\phi(1020)$. In particular, experimental evidence exists for two ω', four ρ' and two ϕ' states. The properties of these resonances can be studied by measuring various final states of hadrons with intermediate resonances. There are still many puzzles and unknown things, therefore clear understanding will require more theoretical and experimental efforts.

Some of the final states (2π, 4π, $\omega\pi$, ...) can be confronted to corresponding τ decays using conserved vector current (CVC) and isospin symmetry. Such a comparison can hopefully help in solving the existing discrepancy between τ decays and e^+e^- annihilation into two and four pions [4,30,31].

We can expect future progress in this field from the J/ψ decays to be studied at the Beijing τ-charm factory now at the commissioning stage. Belle can use its huge statistics for an ISR studies of vectors similar to BaBar, where about 230 fb^{-1} of data have been used for that. Such experiments would be complementary to what is planned to do at the dedicated colliders – VEPP-2000 now commissioned in Novosibirsk and DAPHNE-II – an upgrade of the DAPHNE collider actively discussed in Frascati.

I'm grateful to Koji Hara and Toru Iijima for the excellent organization of the Workshop and their kind invitation.

REFERENCES

1. S.I. Eidelman and S.I. Serednyakov, Nucl. Phys. B (Proc. Suppl.) 131 (2004) 19.
2. B. Aubert *et al.*, Phys. Rev. D 76 (2007) 092005.
3. W.-M. Yao *et al.*, J. Phys. G 33 (2006) 1.
4. M. Fujikawa *et al.*, Phys. Rev. D 78 (2008)

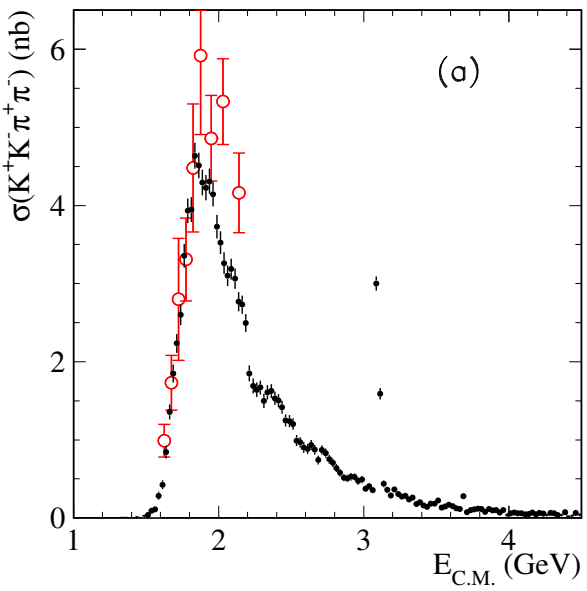

Figure 7. Cross section of the process $e^+e^- \to \phi f_0(980)$

072006.
5. S. Godfrey and N. Isgur, Phys. Rev. D 32 (1985) 189.
6. B. Aubert *et al.*, Phys. Rev. D 77 (2008) 092002.
7. M.N. Achasov *et al.*, Phys. Rev. D 68 (2003) 052006.
8. B. Aubert *et al.*, Phys. Rev. D 70 (2004) 072004.
9. R.R. Akhmetshin *et al.*, Phys. Lett. B 489 (2000) 125.
10. A. Antonelli *et al.*, Z. Phys. C 56 (1992) 15.
11. B. Aubert *et al.*, Phys. Rev. D 73 (2006) 052003.
12. P. Eugenio *et al.*, B 497 (2001) 190.
13. D. Bisello *et al.*, Nucl. Phys. Proc. Suppl. 21 (1991) 111.
14. R.R. Akhmetshin *et al.*, Phys. Lett. 595 (2004) 101.
15. M.N. Achasov *et al.*, JETP 101 (2005) 1053.
16. B. Aubert *et al.*, Phys. Rev. D 71 (2005) 052001.
17. T. Barnes *et al.*, Phys. Rev. D 55 (1997) 4157.
18. A. Donnachie and Yu.S. Kalashnikova, Phys. Rev. D 60 (1999) 114001.
19. S.I. Bityukov *et al.*, Phys. Lett. 188 (1987) 383.
20. V.M. Aulchenko *et al.*, JETP Lett. 45 (1987) 145.
21. A. Abele *et al.*, Phys. Lett. B 415 (1997) 280.
22. P.-L. Frabetti *et al.*, Phys. Lett. B 578 (2004) 290.
23. A. Antonelli *et al.*, Phys. Lett. B 365 (1996) 427.
24. A. Castro *et al.*, Preprint LAL-88-58, Orsay, 1988.
25. M. Ablikim *et al.*, Phys. Rev. Lett. 97 (2006) 142002.
26. F. Mane *et al.*, 112B (1982) 178.
27. J.M. Link *et al.*, Phys. Lett. B 545 (2002) 50.
28. B. Aubert *et al.*, Phys. Rev. D 76 (2007) 012008.
29. M. Ablikim *et al.*, Phys. Rev. Lett. 100 (2008) 102003.
30. M. Davier *et al.*, Eur. Phys. J. C 27 (2003) 497.
31. M. Davier *et al.*, Eur. Phys. J. C 31 (2003) 503.