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M. Greco: ON THE $\lambda\bar{\lambda}$ SPECTROSCOPY IN e^+e^- ANNIHILATION.

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ABSTRACT. -

The properties of the radial excitations of the ϱ, ω and φ mesons are discussed. In particular it is proposed to identify the recently observed states at $\sqrt{s} \simeq 1.5$, 1.82 and 2.13 GeV in e^+e^- annihilation with the $\varphi_D \equiv {}^3D_1(\lambda\bar{\lambda})$, φ'' and φ''' mesons respectively. The φ' meson is suggested to lie in the vicinity of 1.5 GeV and strongly coupled to the φ_D. The $\varrho''(1.6)$ width is also suggested to be smaller than previously reported.

The large number of exited $c\bar{c}$ levels observed[1] in e^+e^- annihilation naturally has led to the question of the existence of radial and possibly orbital exitations of the ϱ, ω and φ mesons and whether they could have escaped observation. First generation experiments at Adone had indeed observed[2] a large multihadronic production in the energy range $1 \lesssim \sqrt{s} \lesssim 3$ GeV. However, the rather small detection efficiency of the various set ups along with a large energy separation of the data points did not allow to disentangle possible structure in specific channels which, on the other hand, could have been responsible for some discrepancies among different experiments. A rather broad $\varrho''(1.6)$[3] and a possible existence of a $\varrho'(1.25)$[4] had been the only indications from storage rings, also consistent with photoproduction experiments[5].

We have recently analyzed[6] the situation in this restricted domain of e^+e^- energies, in particular in the context of the extended vector dominance model[7], which provides the most natural theoretical framework for a discussion of this subject. In fact, the various recorrences of the ϱ, ω, φ and ψ mesons, which in a simple quark model correspond to the $I=0$ radial exitations, extrapolate in average sense the asymptotic value of R ($R \equiv \sigma(e^+e^- \to \text{hadrons})/ (e^+e^- \to \mu^+\mu^-)$), giving a very simple connection between the scaling and the resonant regions. As well known, one predicts

$$R = \sum_{i=\varrho,\,\omega,\,\varphi,\,\psi} \frac{9\pi}{\alpha^2} \frac{m_i(\Gamma_i \to e^+e^-)}{\Delta m_i^2} \simeq 2.5 \pm 1.7 = 4.2\,, \qquad (1)$$

in excellent agreement with experiments. The spacing Δm_i^2 between two near resonances of the type-i is $\Delta m_i^2 \simeq 2m_\varrho^2$ for normal mesons and $\Delta m_\psi^2 \simeq 4\ \text{GeV}^2$ for the ψ family.

The most striking prediction in ref. (6) concerned the expectations of the lowest three members of the φ family, with masses around 1.49, 1.84 and 2.14 GeV respectively. The main point was that the φ', φ'' and φ''' were expected to be rather narrow for both kinematical reasons and the rapid decrease of the form factors of two-body and quasi two-body exclusive channels, producing rather localized activities in e^+e^- total cross section. On the other hand the higher members were expected to get much broader giving rise to a smooth scaling cross section with a step in R of about half unity. On the contrary the various exitations of the ω-family (ω', ω'', ...) were all expected to be rather broad, essentially because of the assumed large decays $\Gamma(\varrho', \varrho'' \to \omega\pi) \gtrsim 100$ MeV and therefore $\Gamma(\omega', \omega'' \to \varrho\pi) \gtrsim 300$ MeV.

Evidence for new vector states has been very recently reported from Adone and DCI at 2.13[8], 1.82[9], 1.5[10] and 1.78[11] GeV respectively. In the light of the previous discussion, the position and the quite small widths of the states observed at Frascati (~ 50, ~ 30 and

$\sim$ 5 MeV) suggest the obvious interpretation as the lowest three radial exitations of the φ meson. Similarly, it is tempting to identify[12] the 5π enhancement seen at Orsay with the ω'', the isoscalar partner of the $\rho''(1.6)$. However questions of various types are raised with these assignements by the properties of the new states. First, the 1.5 state is much too narrow : its width is in fact at least a factor three smaller than any optimistic estimate. Secondly, the combined properties of the $\omega''(1.78)$ and the $\varphi''(1.82)$ are in contradiction,by simple arguments, with the rather broad $\rho''(1.6)$, as it has been reported to be. In addition, increasing evidence[13] for more structures around 1.25 and 1.35 GeV is coming from a pnotoproduction experiment by a DESY-Frascati collaboration which, once identified as the ρ' and ω', have to be considered in the whole picture.

For all these reasons we reconsider here the situation for the various ρ-ω-φ exitations. In particular, we discuss the predictions for the most important decay modes as given by a previous model[14] for radiative decays of mesons. From these results we are led to the following conclusions. The 1.82 and 2.13 states are identified as the φ'' and φ''' mesons. On the other hand the 1.5 is suggested to be the $\varphi_D \equiv {}^3D_1(\lambda\bar{\lambda})$ state, the true φ' being at a lower, but a nearby energy. Furthermore, from the combined properties of the ω'' and φ'' it is argued that the ρ'' width is smaller than what is normally believed.

Let us consider first the decays $\rho', \rho'' \to \omega\pi$. From a previous treatment[14] of radiative decays of old and new $(c\bar{c})$ mesons, which successfully explains the strong suppressions of the decays $\varphi \to \eta\gamma$, $K^* \to K\gamma$ and $\psi \to \eta_c\gamma$, the vertex function for the transition $\gamma(q^2) \to \omega\pi$ is given by

$$F_{\omega\pi\gamma}(q^2) = \frac{2}{\pi} g_{\omega\pi\gamma} B\left[(1 - \alpha(q^2), 3/2\right], \qquad (2)$$

where, as usual, $B(x,y) = \Gamma(x)\Gamma(y)/\Gamma(x+y)$, and $\alpha(q^2)$ is the ρ-trajectory. The expansion of the B-function

$$B(1-\alpha(q^2), 3/2) = \frac{\Gamma(3/2)}{\alpha'} \sum_n \frac{(-1)^n}{n!} \frac{1}{m_n^2 - q^2} \frac{1}{\Gamma(3/2-n)} , \tag{3}$$

gives, for the lowest poles of interest,

$$g_{\varrho\omega\pi} = \frac{2}{\pi e} \frac{f_\varrho}{\alpha' m_\varrho^2} g_{\omega\pi\gamma} , \qquad g_{\varrho'\omega\pi} = -\frac{2}{\pi e} \frac{f_{\varrho'}}{2\alpha' m_{\varrho'}^2} g_{\omega\pi\gamma} ,$$

$$g_{\varrho''\omega\pi} = -\frac{2}{\pi e} \frac{f_{\varrho''}}{8\alpha' m_{\varrho''}^2} g_{\omega\pi\gamma} . \tag{4}$$

The first of these eqs. gives the correct result for the decay $\omega \to \pi\gamma$. From the other two one easily obtains

$$\Gamma(\varrho' \to \omega\pi) = \Gamma(\omega \to \pi\gamma) \left(\frac{p_{\varrho'\omega\pi}}{p_{\omega\pi\gamma}}\right)^3 \left(\frac{1}{\pi e}\right)^2 \left(\frac{f_{\varrho'}}{\alpha' m_{\varrho'}^2}\right)^2 \simeq 40 \ (80) \ \text{MeV}, \tag{5}$$

and

$$\Gamma(\varrho'' \to \omega\pi) = \Gamma(\omega \to \pi\gamma) \left(\frac{p_{\varrho''\omega\pi}}{p_{\omega\pi\gamma}}\right)^3 \left(\frac{1}{\pi e}\right)^2 \left(\frac{f_{\varrho''}}{4\alpha' m_{\varrho''}^2}\right)^2 \simeq 7 \ \text{MeV} . \tag{6}$$

In eq. (5) we have used $m_{\varrho'} = 1.25$ GeV and the two final values of the width (40-80 MeV) correspond to the different estimates $(f_{\varrho'}/m_{\varrho'}) \simeq (f_\varrho/m_\varrho)$ and $(f_{\varrho'}/m_{\varrho'}) \simeq \sqrt{2}(f_\varrho/m_\varrho)$ respectively. The first condition is realized in EVMD(7) and corresponds to exact local duality(7, 15, 16). The second case is suggested by the value of $\Gamma(\psi' \to e^+e^-)$, if the ψ' is assumed as a pure radial exitation. In eq. (6) we have taken $m_{\varrho''} = 1.6$ GeV and $(f_{\varrho''}/m_{\varrho''}) = (f_\varrho/m_\varrho)$. Eq. (5) is consistent with the rather poor knowledge of the ϱ' meson ($\Gamma_{\varrho'} \sim 100$ MeV). On the other hand eq. (6) suggests a largely depressed $\omega\pi$ decay mode of the $\varrho''(1.6)$, in contrast to the common belief. We will get back to this point later.

The decays $\varphi', \varphi'' \to K^*\bar{K}$ are taken into account similarly. We obtain ($\varphi', \varphi'' \sim \lambda\bar{\lambda}$)

$$(\varphi' \to K^*\bar{K}) = 2\Gamma(\varrho' \to \omega\pi)\left(\frac{p_{\varphi' K^* K}}{p_{\varrho'\omega\pi}}\right)^3\left(\frac{m_{\varrho'}}{m_{\varphi'}}\right)^4 \simeq 18 \text{ MeV} , \qquad (7)$$

and

$$(\varphi'' \to K^*\bar{K}) = 2\Gamma(\varrho'' \to \omega\pi)\left(\frac{p_{\varphi'' K^* K}}{p_{\varrho''\omega\pi}}\right)^3\left(\frac{m_{\varrho''}}{m_{\varphi''}}\right)^4 \simeq 4 \text{ MeV} , \qquad (8)$$

where $m_{\varphi'} \simeq 1.5$ GeV, $m_{\varphi''} = 1.82$ GeV and we have assumed $\Gamma(\varrho' \to \omega\pi) \simeq 40$ MeV(x). In eqs. (7-8) the factors $(m_\varrho^{(n)}/m_\varphi^{(n)})^4$ break the simple quark model result and are a consequence of the vertex function (2), on the same footing of the reduction factors found[14] for the decays $\varphi \to \eta\gamma$ and $K^* \to K\gamma$.

In view of a rather small width resulting for the φ' it is convenient to get an estimate of the decays $\varphi' \to 3\pi, 5\pi$ which are forbidden by the OZI-rule[17]. This can be done as follows. From the full $\pi\gamma(q_1^2)\gamma(q_2^2)$ vertex function of reference (14) one can extract the coupling constant $g_{\varrho'\omega'\pi}$, which is found to be

$$g_{\varrho'\omega'\pi} = \frac{9}{2} g_{\varrho'\omega\pi}\left(\frac{f_{\omega'}}{f_\omega}\right)\left(\frac{m_\omega}{m_{\omega'}}\right)^2 \simeq 4 g_{\varrho'\omega\pi} . \qquad (9)$$

Then, assuming for $\omega' - \varphi'$ the same $\omega - \varphi$ mixing, namely

$$\frac{g_{\varphi'\varrho'\pi}}{g_{\omega'\varrho'\pi}} = \frac{g_{\varphi'\varrho\pi}}{g_{\omega'\varrho\pi}} = \frac{g_{\varphi\varrho\pi}}{g_{\omega\varrho\pi}} \simeq 0.05 , \qquad (10)$$

one easily founds, from eqs. (4) and (9),

$$\Gamma(\varphi' \to 3\pi) \simeq \Gamma(\varphi' \to \varrho\pi) \simeq 2.5 \times 10^{-3}\,\Gamma(\omega' \to 3\pi)\,\frac{(\text{Ph - sp})_{\varphi' \to 3\pi}}{(\text{Ph - sp})_{\omega' \to 3\pi}} \simeq \qquad (11)$$

$$\simeq 1 \text{ MeV} ,$$

(x) - All our estimates will be based hereafter on this assumed rate.

$$\Gamma(\varphi' \to 5\pi) \simeq \Gamma(\varphi' \to \varrho'\pi) \simeq 16\,\Gamma(\varphi' \to \varrho\pi)\,\frac{(\mathrm{Ph-sp})_{\varphi' \to 5\pi}}{(\mathrm{Ph-sp})_{\varphi' \to 3\pi}} \approx 4\ \mathrm{MeV}, \tag{11}$$

where $m_{\omega'} \simeq 1.35$ has been assumed, and $\Gamma(\omega' \to \varrho\pi) \simeq 120$ MeV from eq. (5). Finally, from the experimental information[18] of a rather small branching fraction (Br $\lesssim$ 10%) of $\varrho'(1.25) \to \pi\pi$ one gets $\Gamma(\varphi' \to K\bar{K}) \lesssim 2$ MeV.

From all the above results, the total width of the φ' meson, with $m_{\varphi'} = 1.5$ GeV, is estimated $\Gamma(\varphi' \to \mathrm{all}) \simeq 25$ MeV, with a fraction of about 20% in OZI-forbidden decays, as in the case of the φ meson. Comparing with the experimental width of ~ 5 MeV of the recently observed structure at 1.5 GeV[10], the identification of that state with a φ' seems therefore very unlikely. Notice also that our estimates are already a factor of two smaller than those obtained in the case of exact symmetry (see eq. (7)).

On the other hand the position of the observed structure which is almost degenerate with the expected φ', and the very sharp drop of the cross section after the peak are very suggestive of strong interference with a nearby state. Therefore we are naturally led to identify the 1.5 structure with the $^3D_1(\lambda\bar{\lambda})$ state, which would be in a non relativistic quark model essentially degenerate with the $1 = 0$ first radial exitation.

As well known, a $^3D_1$ state can couple appreciably to e^+e^- via a mixing with an $^3S_1$ state, which can be induced by the presence of tensor forces. The mixing parameter ε is defined by $\varepsilon \equiv \langle {}^3D_1 | V_T | {}^3S_1 \rangle / \left[m({}^3S_1) - m({}^3D_1) \right]$[19]. In charmonium the mixing between the $\psi'(3.68)$ and the $^3D_1(3.78)$ has been estimated[19] to be a few percent. Naive extrapolation of those non-relativistic calculations to the $(\lambda\bar{\lambda})$ system, with $m({}^3S_1) - m({}^3D_1) \approx 20$-$30$ MeV suggests indeed quite a large mixing between the 1.5 and nearby φ'. In fact, the matrix element $\langle {}^3D_1 | V_T | {}^3S_1 \rangle$ is proportional to (α_s / m^2), where α_s is the strong quark-gluon coupling constant and m is the quark mass.

Therefore, for all these various reasons, the $^3S_1$ - $^3D_1$ mixing is expected here to be stronger than in charmonium. Of course the φ' should be located not too far from 1.5 GeV, as expected from the naive mass formulae which, on the other hand, seem to work nicely for the φ'' and φ'''. Finally notice that the φ' width can be even smaller than that estimated for $m_{\varphi'}$ = 1.5 GeV, due to vicinity of the $K^*\bar{K}$ threshold. For example, for $m_{\varphi'} \simeq 1.47$ one finds a reduction factor of 0.6 for the result of eq. (7).

Let us discuss now the properties of the ϱ'' - ω'' - φ'' mesons. In the philosophy of a broad ϱ'', with an important $\omega\pi$ decay mode ($\Gamma(\varrho'' \to \omega\pi) \sim 100$ MeV) it would be inconceivable to have $\Gamma_{\omega''} \sim 150$ MeV. Similarly one would have expected $\Gamma_{\varphi''} \sim 50$-100 MeV. However, both the experimental evidences for the 1.78[11] and 1.82[9] states and the results of eqs. (6) and (8) lead to the conclusion of the almost absence of the decay mode $\varrho'' \to \omega\pi$ and the related ones $\omega'' \to \varrho\pi$ and $\varphi'' \to K^*K$. This in turn suggest the possibility that the ϱ''meson is not so broad as previously reported, a possible overlap of different structures being the origin of the observed effect.

Then assuming $\Gamma(\varrho'' \to \varrho\varepsilon) \approx 100$ MeV, with ε being an SU(3) singlet, one roughly estimates[20] $\Gamma(\omega'' \to \omega\varepsilon) \sim \Gamma(\varrho'' \to \varrho\varepsilon)$ and $\Gamma(\varphi'' \to \varphi\varepsilon) \sim \frac{1}{3}\Gamma(\varrho'' \to \varrho\varepsilon)$. Of course, if the decay $\varrho'' \to \varrho\pi\pi$ does not proceed via an ε-coupling, or if the ε is not an SU(3) singlet, but for example $\varepsilon \sim (p\bar{p} + n\bar{n})/\sqrt{2}$, the decay $\Gamma(\varphi'' \to \varphi\pi\pi)$ would be very much depressed via the OZI rule. A direct measurement of the decay $\varphi'' \to \varphi\pi\pi$ is therefore very interesting for a test of various theoretical ideas on the nature of the ε, and also for a comparison with what is known from $\psi' \to \psi\pi\pi$.

The dynamical suppression of the decays $\varphi'' \to \varphi\eta$ ($\sim \frac{1}{2} K^*\bar{K}$), $\varphi'' \to K\bar{K}$ ($\varrho'' \to \pi\pi \lesssim 5\%$), and kinematical suppression of decay modes as $K^*\bar{K}^*$, $K^{*\prime}\bar{K}$, . . . , together with the above discussion on the $\varphi\pi\pi$ mode, explains therefore the observed φ'' small width, leaving at the same time enough space for OZI-inhibited decays which can be of the order of (15-20)%, as for the φ and φ' mesons.

Finally, in addition to the decay mode $\omega\varepsilon$, the large $\varrho''\omega''\pi$ coupling constant $(g_{\varrho''\omega''\pi} \sim g_{\varrho\omega\pi})$(14) can lead to a non negligible decay $\omega'' \to \varrho''\pi$ if one takes into account the ϱ'' width ($\Gamma(\omega'' \to \varrho''\pi) \sim$ ~ 20 MeV). Needless to say that a new accurate measurement of the decay $\varrho'' \to \varrho\pi\pi$ is rather important for the understanding of the combined properties of the V" 's.

As for as the φ''' is concerned, a detailed study of various final states leading for example to $\varphi''' \to K^*\bar{K}\pi\pi$, $K^*\bar{K}\pi^+\pi^-\pi^0$, as $\varphi''' \to$ $\to \varphi'\varepsilon$, $\varphi'\eta$, $K^{*\prime}\bar{K}^*$, together with the dynamical suppression of the decays $K^*\bar{K}$, $\varphi\eta$, $\varphi\varepsilon$, ... suggest a rather small width for this state ($\Gamma \sim 50$ MeV), as already anticipated in ref. (6). Therefore the observation of resonant K^* production at $\sqrt{s} \sim 0.13$ GeV(8), with $\Gamma \sim 30$ MeV, agrees with that prediction and naturally leads to identify this narrow enhancement with the third radial exitation of the φ meson.

The production cross sections for the various recorrences are easily estimated by local duality(16). For the $\varphi^{(n)}$ for example, one obtains from (1)

$$\int s\,\sigma_n(s)\,ds \simeq 12\pi^2 m_\varphi \Gamma(\varphi \to e^+e^-) \, . \qquad (12)$$

On the other hand the integrated cross section over the $^3D_1$ level can be an important fraction of the r. h. s. of (12), if a strong mixing with the $^3S_1$ state is occurring. Similarly the peak cross sections are given by

$$\sigma^{(n)}_{peak} \simeq \left[m_\varphi / m_{\varphi(n)} \right]^3 \left[\Gamma_\varphi / \Gamma_{\varphi(n)} \right] \sigma^\varphi_{peak} \, , \qquad (13)$$

with $\sigma^\varphi_{peak} \simeq 4\ \mu b$. They are therefore in the range of 100 nb.

In conclusion we have given various arguments for identifying the recently observed states of $\sqrt{s} \approx 1.5$, 1.82, 2.13 and 1.72 with the $\varphi_D \equiv {}^3D_1(\lambda\bar{\lambda})$, φ'', φ''' and ω'' respectively. A narrow φ' is expected around 1. 5 GeV, strongly mixed with the $^3D_1$ level. The $\rho''(1.6)$ width is also suggested to be smaller than previcusly reported. Further and accurate experiments in this e^+e^- energy domain are therefore highly desirable. In particular a detailed study of the final state configurations will be of great help for a better understing of the $\lambda\bar{\lambda}$ system and its comparison with the $c\bar{c}$ dynamics.

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