ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-76/55(R)
10 Novembre 1976

M. Greco : ON e^+e^- ANNIHILATION AT MODERATE ENERGIES. -

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In view of the future experimental programs in e^+e^- annihilation at moderate energies ($2E \lesssim 3$ GeV) we briefly review here the present situation in this field, with particular emphasis on those questions which require further experimental investigations.

The standard three-triplet model of fractionally charged quarks provides the theoretical framework for the present discussion. Threshold considerations allow us to disregard charmed quarks. Of course the extensive information on this new degree of freedom, as for example ψ spectroscopy, the decay modes of the various levels, the sudden increase in R, etc., does have precise implications for the old physics, at least as a frame of reference for various theoretical questions which there find many clear answers.

Defining the total cross section in terms of hadronic vacuum polarization as

$$\sigma_{had}(s) = \frac{4\pi\alpha}{s} \operatorname{Im} \pi(s) , \qquad (1)$$

where $s = 4E^2$, one can theoretically distinguish two distinct regions. At low energies various 1^{--} resonances can be excited, and in the narrow width approximation,

$$\operatorname{Im} \pi(s) \underset{s \approx m_V^2}{\sim} 4\pi^2\alpha \frac{m_V^2}{f_V^2} \delta(s - m_V^2) , \qquad (2)$$

where em_V^2/f_V defines the coupling of the vector state to the photon.

The ρ, ω, φ and J/Ψ mesons are the lowest typical example of a fauna which should grow rapidly as soon as their radial exitatitions are included. At sufficiently high energies the scaling regime should take over, and one has

$$\mathrm{Im}\,\pi(s) \longrightarrow \frac{\alpha}{3} R , \tag{3}$$

where R is the usual ratio $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$. As well known the naive parton model result

$$R = \Sigma_i Q_i^2 = 2 \tag{4}$$

is obtained as the leading order term in asymptotically free field theories (AFFT)[1]. These theories explicitly predict the approach to asymptotia, namely

$$R = \Sigma_i Q_i^2 \left(1 + \frac{c}{\ln(s/\mu^2)} + \cdots \right), \tag{5}$$

where c is a positive constant depending on the specific theory[1, 2].

In the extended (or generalized) vector dominance model[3] (EVMD) furthermore the value of R is explicitly given in terms of the low energy parameter f_ρ,

$$R = \sum_{i=\rho,\omega,\varphi} \frac{9\pi}{\alpha^2} \frac{m_i(\Gamma_i \to e^+e^-)}{\Delta m_i^2} \simeq \frac{8\pi^2}{f_\rho^2} \simeq 2.5 , \tag{6}$$

with $\Delta m_i^2 \simeq 2m_\rho^2$. This expression roughly agrees with (4). Experimentally[4] one finds $R \simeq 2.5$, in excellent agreement with (6), and to within $\sim 20\%$ of the prediction of (4)[(x)]. So far the quality of data does not permit a verification of the specific form of the approach to scaling given by AFFT (eq. (5)). However the analyses[5] of scaling

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(x) - Experimental deviations from the standard result $R = \Sigma Q_i^2$ at a level of about 20% can be misleading in the interpretation of the data, when the number of quarks is increasing. For example, the inclusion of charm leads to $R = 3\,1/3$ instead of (4), whereas (6) is modified and gives $R \simeq 4.2$. Experimentally and assuming the existence of an heavy lepton one has $R \simeq 4\text{-}4.5$[4]. In the standard model this result could imply the existence of additional degrees of freedom.

violations observed in deep inelastic electro- and neutrino-scattering indicate qualitative agreement with the specific features predicted by AFFT, analogous to those of (5). In the future a direct test of (5) would be very interesting. This of course implies very accurate measurements of the total cross section.

Given the low and high energy regions the question naturally arises as to whether there exist any connection between them. That is, is the excitation of a resonance related to an intrinsic property like the quark charge? The question does have an important experimental consequence for obvious reasons, since a given plateau would imply the existence of lower states and therefore a resonance search program, and viceversa.

The answer to that question has been given in the framework of EVMD, where it has been shown[6] that the following sum rule is identically satisfied:

$$\int_{s_0}^{\infty} (\mathrm{Im}\,\pi(s) - \frac{\alpha R}{3})\, ds = 0 . \tag{7}$$

More generally the r.h.s. of eq. (6) is given by a constant which depends in a given model upon the softness of the energy momentum tensor. In the above model this duality sum rule holds at a local level also, i.e. the various radial exitations of different species averaged over an interval $\Delta s \sim 2\, m_\rho^2$ give the asymptotic ratio R. Experimentally eq. (7) is certainly satisfied at the level of the ρ, ω, φ and J/ψ resonaces (for the ψ particles, $\Delta s \sim 4$ GeV^2). The available information on the ρ'' is also consistent with it. The non trivial content of (7) follows directly from the fact that the observed values of R at the peak of the best known resonances are in the range of 10-100.

In the spirit of eq. (7), and also at the light of the observed ψ spectroscopy ($\psi'(3700)$, $\psi''(4100)$, ...) the question arises as to where are the various exitations of ρ, ω, and φ and why have they escaped observation. With this in mind we will briefly review the theoretical expectations on these states as well as the corresponding experimental situation.

The $\rho'(1250)$ has the longest history[7] and a number of observations have been reported. In addition to photoproduction experiments and $p\bar{p}$ annihilation at rest, which have given indirect support to it, the reactions $e^+e^- \to \pi^+\pi^-$ and $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ are the best candidates for its observation. However, because of the small branching ratio into $\pi^+\pi^-$ (B.R. $\approx$ 5-10%), the observed deviations[8,9] from the Gounaris-Sakurai tail of the π meson form factor are not conclusive. A possible alternative explanation is simply a unitarity reflection of the opening of multipion channels. The second reaction remains therefore the cleanest source for definite evidence. In spi te of previous indications from Novosibirsk[10] and Frascati[11], with peak cross sections of the order of 80 nbs, a recent experiment at VEPP2M[9] has not given conclusive evidence in this regard. The observed cross section however is much higher that should be expected from the ρ-tail (a few nb) and from $1/2\ \sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^-)$, if simple $\rho\varepsilon$ production is assumed, where ε simply indicates an S-wave $(\pi\pi)$ system. A further and, hope fully, final detailed explo ration of this energy region is therefore highly desirable. The peak cross section, for $\Gamma_{\rho'} \simeq 150$ MeV, is givan by

$$\sigma_{\rho'}^{peak} \simeq \sigma_{\rho}^{peak} \left(\frac{m_\rho}{m_{\rho'}} \right) \left(\frac{f_\rho}{f_{\rho'}} \right)^2 , \tag{8}$$

which has a value of 150-200 nb if $(f_{\rho'}/f_\rho)^2 \simeq (m_{\rho'}/m_\rho)^2$. However this simple scaling law, which asymptotically follows in EVMD, does not seem to work at the level of the first radial exitations. For com parison one finds $(f_{\psi'}/f_\psi)^2 \simeq 2(m_{\psi'}/m_\psi)^2$. Therefore the peak cross section is expecetd to have a value in the range of (50-100) nb. As a final remark we observe that an analysis[12] of the nucleon form factors also suggest evidence for an isovector state at a mass near 1250 MeV.

The situation of $\rho''(1600)$ is much healthier. In addition to the evidence in e^+e^- annihilation[13], various photoproduction experiments[14] have given further support to it, and also other indications have come from phase-shift analysis of $\pi\pi$ scattering[15]. Fur ther experimental efforts in this field are also necessary, in order to clarify the situation at least in two respects. First the recent da ta[9] from Novosibirsk in the reaction $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ suggest the production of a non resonating background starting from 1.1-1.2 GeV, at a level higher than the previous Frascati indications, and comparable with the observed ρ'' peak cross section[13]. Furthermore clear information on the different decay modes, including a possible substantial $\pi\omega$ fraction, is still missing. This in turn will give a better determination of the coupling constant to the photon.

As far as higher isovector exitations are concerned, they are expected to be rather broad ($\Gamma_i \gtrsim 500$ MeV). It seems therefore hopeless to observe them individually, the overall effect being of course a smooth scaling behaviour for the cross section.

A very similar situation is expected for the various exitations of the ω meson (ω', ω'', ..). Roughly we have in fact $\Gamma_{\omega'} \approx 3\,\Gamma_{\rho'} \approx 400$ MeV for $m_{\omega'} \simeq 1250$ and larger widths for the higher states. In addition, the $\omega^{(n)}$ have couplings to the photon that are nine times smaller than the corresponding $\rho^{(n)}$. The overall contribution is expected therefore to scale very soon.

Let us consider now the expectations for the various members of the φ family. As we will see below the situation here is rather interesting principally because of the experimental implications. According to a quadratic mass fromula $m_n^2 = m_o^2 + n\,\Delta m^2$, with $\Delta m^2 \simeq 2\,m_\rho^2$, one finds the following spectrum

$$m_1 = 1.49\,, \quad m_2 = 1.84\,, \quad m_3 = 2.14\,, \quad m_4 = 2.4\,, \ldots \qquad (9)$$

which has to be taken of course "cum grano salis". The main point is that the φ', φ'' and φ''' are expected to be reasonably narrow ($\Gamma_i \sim 50$-100 MeV), producing rather localized activity in e^+e^- total cross section. On the other hand the higher members due to the opening of various channels with four kaons, should be much broader. The resulting effect is an overall contribution to σ_{tot}, which is also due to the increasing density of the levels. One should therefore observe an increase of R of about $(2/12) \times 2.5 \simeq 0.5$, with a threshold at $\sqrt{s} \simeq 2.2$-2.3 GeV(16). This would be analogous, but less impressive, to that observed(4) at $\sqrt{s} \gtrsim 4$ GeV, due to the full opening of the charmed degree of freedom. A corresponding increase in the number of k's also should be observed.

In more detail the main decay mode of the φ' is represented by the $(k^*\bar{k} + \bar{k}^*k)$ channel; the threshold of which is rather near ($\sqrt{s} \simeq 1.4$ GeV). A small variation from 1.49 GeV is the mass of φ' will therefore affect considerably the total width. With a small contribution of the $k\bar{k}$ mode the resulting width is expected to be of the order of 50 MeV(17,18).

Using an explicit model(19) for the vertices V_nVP and V_nVS, and also through the available information on $\rho'' \to \rho\pi\pi$, one can similarly estimate a width for the φ'' of ~ 100 MeV(20). The decay $\varphi'' \to \varphi\varepsilon$, where ε indicates an S-wave $\pi\pi$ system with an effective mass of about 600 MeV, should be a good signature for experimental observation.

Similarly the decays $\varphi''' \to V'S$ and $V'P$ should be the main decay modes of the third radial exitation of the φ in that the decays VP or VS are more depressed. The resulting width should be near 50 MeV, with decays of the type $\varphi''' \to \varphi'\varepsilon$ or $\varphi''' \to \varphi'\eta\,(\varphi' \to k^*\bar{k})$ as good candidates for the detection of this resonant state.

With the above estimates the corresponding peak cross sections should be of order of 50 nbs for all three states, and that should make them reasonably easy to observe.

It seems appropriate to discuss here the implications of a recent experimental result(21) in photoproduction of electron pairs in the mass region $1 \lesssim M \lesssim 2$ GeV, where M is the invariant mass of the e^+e^- system. In addition to various possible structures for M between 1.2 and 1.8 GeV, a single structure is significantly observed at $M \simeq 1.11$ GeV, with a width $\lesssim 30$ MeV (mass resolution of the apparatus), and at a level of 5% of the φ meson, i.e. $[Br \times (d\sigma/dt)_{t=0}]_{1.1}/[Br \times (d\sigma/dt)_{t=0}]_{\varphi} \simeq 1/20$. On the other hand nothing has been observed in e^+e^- annihilation at VEPP2M(9) in the same mass region, although the spacing of the data points (~ 25 MeV) could still have allowed a narrow spike not to be observed. The situation therefore has to be clarified. From a theoretical point of view a possible identification of this 1.1 signal with a φ' seems very unlikely for reasons of mass, whereas an ω' of 1.1 GeV would be much broader. For example, from the model of ref. (19) we find $\Gamma(\omega' \rightarrow 3\pi) \simeq 50$ MeV $(f_{\omega'}/f_{\omega})^2 \approx 100$-$200$ MeV for $m_{\omega'} = 1.1$ GeV.

A very appealing possibility for the interpretation of the above result is offered by the Pati-Salam model(22) of lepton-hadron unification. One of the main consequences of this unconfined colour gauge theory is that both quarks and gluons can be directly produced in e^+e^- annihilation. In particular the lightest of the colour gluons could have a mass of (1-2) GeV and should show itself as a peak in the total cross section. The corresponding total width and branching ratio for e^+e^- decay are estimated in the ranges 1-10 MeV and B.R. $\sim 10^{-3}$ respectively. Its production should be therefore comparable to that of the φ meson.

In view of the great interest in such a theory and the various fondamental implications as well as the many phenomenological consequences it appears very important to carry out a detailed search program for narrow structures in the low energy domain. This would be particularly important in case of possible incomplete answers from current experiments.

So far we have concentrated our discussion on those questions which are, in our opinion, most important in order to clarify our understanding of the so called old physics and complete the very simple scheme which also nicely fits the new e^+e^- phenomena. It is clear however that many other aspects which eventually have been partially examined in first generation experiments, as for example meson and nucleon form factors, exclusive final states, the behaviour of one particle inclusive distributions at smaller energies, etc., need to be studied in more detail, in order to have a global understanding of what is going on in e^+e^- physics.

For all the above reasons new and extensive experimental efforts in the near future in the low energy domain of e^+e^- annihilation are highly desirable.

I am grateful to F. Felicetti, H. Genz and C. Mencuccini for many valuable discussions, and to G. T. Zorn for a critical reading of the manuscript.

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