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Hadron Production in e^+e^- Collisions and the Existence of New Vector Mesons.

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Recently some experimental effort has been devoted to search for additional vector mesons whose existence has been suggested by many theoretical models (1). Different experiments (2) looking at coherent photoproduction of high-mass pion pairs from nuclei have shown some evidence for a broad resonance in the mass range (1.4÷1.6) GeV, although none of them has unambiguously established its mass and width. Furthermore the analysis of the four-pion mass spectrum produced in the reaction $\gamma p \to \pi^+\pi^-\pi^+\pi^- p$ shows an enhancement at 1.55 GeV having a width of (0.26 ± 0.11) GeV (3,4).

In the present letter we assume the existence of a meson having the quantum numbers of the ρ, we call it ρ', and we discuss some consequences of its existence. First we re-examine the situation concerning the decays of the known pseudoscalar and vector mesons taking into account the contributions of the ρ' and its SU_3 partners. This enables us to have an estimate of how these new mesons couple to the photon and to the old ones. We study then the cross-sections for production of hadrons in e^+e^- collisions and predict their magnitude and behaviour at total energies of the colliding beams $2E$ ranging from 1.4 to 2.4 GeV.

A general analysis of the VMD predictions concerning the electromagnetic and strong decays of the known mesons has been recently made (5) showing that a reasonable agreement with the experimental data can be achieved. We now reconsider the whole

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(1) N. N. KHURI: *Phys. Rev.*, **132**, 914 (1963); D. Z. FREEDMAN and J. M. WANG: *Phys. Rev.*, **153**, 1596 (1967); G. VENEZIANO: *Nuovo Cimento*, **57** A, 190 (1968); J. A. SHAPIRO: *Phys. Rev.*, **179**, 1345 (1969); H. L. LIPKIN: *Proceedings of the Lund International Conference on Elementary Particles* (Lund, 1970).

(2) *a*) G. MCCLELLAN, N. MISTRY, P. MOSTEK, H. OGREN, A. OSBORNE, A. SILVERMAN, J. SWARTZ, R. TALMAN and G. DIAMBRINI-PALAZZI: *Phys. Rev. Lett.*, **23**, 718 (1969); *b*) F. BULOS *et al.*: SLAC-PUB-751 (1970); *c*) H. ALVENSLEBEN, U. J. BECKER, W. K. BERTRAM, M. CHEN, K. J. COHEN, R. T. EDWARDS, T. M. KNASEL, R. MARSHALL, D. J. QUINN, M. ROHDE, G. H. SANDERS, H. SCHUBEL and S. C. C. TING: *Phys. Rev. Lett.*, **26**, 273 (1971).

(3) M. DAVIER *et al.*: SLAC-PUB-666 (1969).

(4) For a review of the experimental situation see R. MARSHALL: *Proceedings of the Daresbury Study Weekend* (June 1970).

(5) A. BARACCA and A. BRAMÒN: *Nuovo Cimento*, **69** A, 613 (1970).

situation along the same lines by including these new vector mesons in order to estimate the value of some of their coupling constants.

The ρ-photon, ρ′-photon couplings and the coupling constants among the different SU_3 multiplets involved in our model are defined as follows:

$$g_{\rho\gamma} = em_\rho^2/f_\rho\,, \qquad g_{\rho'\gamma} = em_{\rho'}^2/f_{\rho'}\,, \tag{1}$$

$$\begin{cases} g = g_{\rho\rho\eta_8}\,, & h = g_{\omega_1\rho\eta_8}\,, \quad f = -g_{\rho\rho\eta_1}\,, \\ g' = g_{\rho\rho'\eta_8}\,, & h' = g_{\omega_1\rho'\eta_8}\,, \quad f' = -g_{\rho\rho'\eta_1}\,. \end{cases} \tag{2}$$

By means of the usual techniques of VMD and SU_3 we obtain the decay rates for processes of the type $V \to 3\pi$, $V \to \pi\gamma$ and $P \to \gamma\gamma$ in terms of the products (*) g/f_ρ, $g'/f_{\rho'}$, h/f_ρ and $h'/f_{\rho'}$. From the experimental values (6) $\Gamma(\omega \to 3\pi) = 11.7$ MeV, $\Gamma(\varphi \to 3\pi) = 0.73$ MeV, $\Gamma(\omega \to \pi^0\gamma) = 1.12$ MeV and $\Gamma(\varphi \to \pi^0\gamma) \simeq 0$ (< 0.014 MeV) and taking the ω-φ mixing angle as predicted by the quark model, *i.e.* $\sin\theta = 1/\sqrt{3}$, we obtain the following values expressed in $(\text{GeV})^{-1}$:

$$\frac{eg}{f_\rho} = 0.59\,, \qquad \frac{eh}{f_\rho} = 0.91\,, \qquad \frac{eg'}{f_{\rho'}} = -0.09\,, \qquad \frac{eh'}{f_{\rho'}} = -0.19\,. \tag{3}$$

We check these results by evaluating the decay rate of the neutral pion. We obtain $\Gamma(\pi^0 \to \gamma\gamma) = 8.4$ eV in good agreement with the value $\Gamma(\pi^0 \to \gamma\gamma)_{\text{exp}} = (8.5 \pm 1.7)$ eV quoted in ref. (6). We note that the introduction of the new mesons, their couplings being $(10 \div 20)\%$ of the old ones, may be considered as a rather small correction to the original VMD results.

In order to estimate the coupling constants f/f_ρ and $f'/f_{\rho'}$ we need to consider processes involving the η and η′ mesons for which the theoretical and experimental situation is not so clear. Assuming an η-η′ mixing angle $\alpha = 10.4°$ and taking the experimental results (6) $\Gamma(\eta \to \gamma\gamma) = 1.01$ keV and $\Gamma(\eta \to \pi^+\pi^-\gamma) = 0.127$ keV we deduce

$$ef/f_\rho \simeq -0.14\ (\text{GeV})^{-1}\,, \qquad ef'/f_{\rho'} \simeq 0.84\ (\text{GeV})^{-1}\,. \tag{4}$$

A new check of our values (3) and (4) is again possible by evaluating the radiative decay rates of the η′-meson. We find $\Gamma(\eta' \to \gamma\gamma) \simeq 54$ keV and $R \equiv \Gamma(\eta' \to \pi^+\pi^-\gamma)/\Gamma(\eta' \to \gamma\gamma) \simeq 2.4$ in good agreement with the more recent experimental results (7) from which the values $\Gamma(\eta' \to \gamma\gamma)_{\text{exp}} < 400$ keV and $R_{\text{exp}} \simeq 2.5$ can be easily deduced. We note from eqs. (4) that the ρ′ gives now an essential contribution to reduce the value $R \simeq 14$ previously obtained in ref. (5). We finally emphasize that all the above results do not depend on the exact value of the ρ′ mass and width we have used, provided $m_{\rho'} \gtrsim 2m_\rho$.

We proceed now to investigate the implications of the ρ′ in the production of hadrons in e^+e^- annihilation. The total cross-section for $e^+e^- \to \rho' \to$ (final state f) at a total energy $2E = \sqrt{s}$ around the mass of the ρ′ is given by

$$\sigma_f(s) = 16\pi^2\alpha^2 \frac{m_{\rho'}^4}{f_{\rho'}^2} \frac{1}{s^{\frac{3}{2}}} \frac{\Gamma_{\rho' \to f}}{(s - m_{\rho'}^2)^2 + m_{\rho'}^2 \Gamma_{\rho'}^2}\,, \tag{5}$$

(*) Amplitudes involving the ratio $f_\rho^2/f_{\rho'}^2$, which we find to be small, have been neglected at this early stage.

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(7) J. BENSINGER, A. R. ERWIN, M. A. THOMPSON and W. D. WALKER: *Phys. Lett.*, **33** B, 505 (1970). See also D. BOLLINI, A. BUHLER-BROGLIN, P. DALPIAZ, T. MASSAM, F. NAVACH, F. L. NAVARRIA, M. A. SCHNEEGANS and A. ZICHICHI: *Nuovo Cimento*, **58** A, 289 (1968).

where $f_{\rho'}$ is defined in eq. (1), $\Gamma_{\rho'\to f}$ is the decay rate for $\rho'\to f$ and $\Gamma_{\rho'}$ is the ρ' total width. From the experimental evidence we roughly assume $m_{\rho'}\simeq 1.5$ GeV and $\Gamma_{\rho'}\simeq 0.35$ GeV. Let us consider first the final state f which gives rise to high multiplicities of produced particles and can be related to the above discussion on meson decays, namely $\omega\pi$, $\varphi\pi$, $\rho\eta$ and $\rho\eta'$. From eq. (5) it follows that the different production cross-sections depend only on the ratio $\Gamma_{\rho'\to f}/f^2_{\rho'}$, which, apart from phase-space factors, can be computed using the results of eqs. (3) and (4). We are therefore able to predict the magnitude and the energy behaviour of the total cross-sections in the energy region around the mass of the ρ'.

By means of the usual techniques to evaluate the partial decay rates we get the following values for the different peak cross-sections:

$$(6)\qquad \begin{cases} \sigma_{e^+e^-\to\omega\pi}(m^2_{\rho'}) = 3.6\ \cdot 10^{-32}\ \text{cm}^2\,, & \sigma_{e^+e^-\to\rho\eta}\ (m^2_{\rho'}) \simeq 0.2\cdot 10^{-32}\ \text{cm}^2\,,\\ \sigma_{e^+e^-\to\varphi\pi}(m^2_{\rho'}) \simeq 0.07\cdot 10^{-32}\ \text{cm}^2\,, & \sigma_{e^+e^-\to\rho\eta'}(m^2_{\rho'}) = 0.1\cdot 10^{-32}\ \text{cm}^2\,. \end{cases}$$

The energy dependence of the total cross-sections for $\omega\pi$ and $\rho\eta'$ production in the range $1.4\leqslant\sqrt{s}\leqslant 2.4$ is shown in Fig. 1. It is clear from this figure that the mode $e^+e^-\to\omega\pi$ dominates all other modes near the $m_{\rho'}$ peak, while the channel $\rho'\to\rho\eta'$

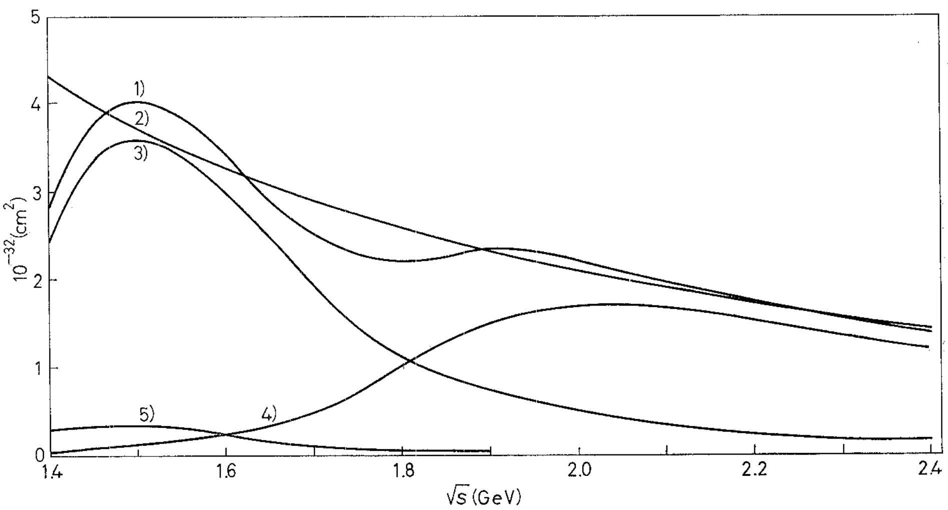

Fig. 1. – Curve 1) $\omega\pi^0+\rho\eta'+\pi^+\pi^-$, curve 2) $\mu^+\mu^-$, curve 3) $\omega\pi^0$, curve 4) $\rho\eta'$, curve 5) $\pi^+\pi^-$.

opens at 1.7 GeV approximatively and dominates thereafter. The $\varphi\pi$ and $\rho\eta$ modes are depressed because of the smallness of their coupling constants. The multiplicities produced in the final state are easily found to be

$$\omega\pi^0 \begin{cases} \pi^+\pi^-\pi^0\pi^0\,, & 90\%\,,\\ \pi^0\pi^0\gamma\,, & 10\%\,, \end{cases}$$

$$\rho\eta' \begin{cases} \pi^+\pi^-\quad +\text{neutrals}\,, & 26\%\,,\\ 2(\pi^+\pi^-)+\text{neutrals}\,, & 62\%\,,\\ 3(\pi^+\pi^-)+\pi^0\ \text{or}\ \gamma\,, & 12\%\,. \end{cases}$$

As far as the reaction $e^+e^- \to \rho' \to \pi^+\pi^-$ is concerned, for which the previous considerations cannot apply, it is possible to extract some information from the experimental results on pion pair photoproduction from nuclei [2]. By assuming that the enhancement observed in ref. [2c] is due to the ρ' and from the fact that the interference between ρ and ρ' at the $m_{\rho'}$ peak is small we obtain (*)

$$\frac{\Gamma_{\rho'\to\pi\pi}}{\Gamma_{\rho'}} \simeq 0.006 \frac{\Gamma_{\rho'}}{\Gamma_\rho} \frac{f_{\rho'}^2}{f_\rho^2} \tag{7}$$

and therefore $\Gamma_{\rho'\to\pi\pi}/\Gamma_{\rho'} \simeq 5.6\cdot 10^{-4} f_{\rho'}^{-2}$. Substituting in eq. (5) we find for the cross-section at the peak $\sigma_{e^+e^-\to\pi^+\pi^-}(m_{\rho'}^2) \simeq 0.36\cdot 10^{-32}\ \text{cm}^2$. The energy dependence of $\sigma_{\pi^+\pi^-}(s)$ is shown in Fig. 1. The ρ' resonant contribution to the process $e^+e^- \to K^+K^-$ is obtained from the preceding reaction $e^+e^- \to \pi^+\pi^-$ by assuming SU_3 symmetry. We find $\sigma_{K^+K^-}(m_{\rho'}^2) \simeq 0.09\cdot 10^{-32}\ \text{cm}^2$. By adding the cross-sections $\sigma_f(s)$ for the states f above considered we give in Fig. 1 the total cross-section which is compared to the theoretical behaviour of $\sigma_{e^+e^-\to\mu^+\mu^-}(s)$. It is striking to note how the different channels add together for $\sqrt{s} \gtrsim 1.5$ GeV to give in good approximation a cross-section behaving as $1/s$.

We add some remarks, also in order to clarify the limits of our model. By assuming the existence of a new vector meson having a mass about 1.5 GeV we have shown that the theoretical status of the known meson decays is improved. The cross-sections for $e^+e^- \to$ hadrons in the range $1.4 \leqslant \sqrt{s} \leqslant 2.4$ GeV have been then predicted. However, we have so far neglected interference contributions coming mainly from $e^+e^- \to \rho \to \omega\pi$ and $e^+e^- \to \rho \to \pi^+\pi^-$ [8]. These additional terms, which are negligible on the ρ' peak, can be present particularly for c.m. energies smaller than $m_{\rho'}$. They can change slightly our results which represent the main contribution to the production cross-sections. We have also disregarded final states like $\rho' \to A_1^\pm\pi^\mp$ or more sophisticated ones because of the lack of a clear experimental and theoretical situation, avoiding in this way the introduction of unknown free parameters. A precise evaluation of these extra terms should come from a detailed comparison with experiments.

An accurate knowledge of the total peak cross-section will lead to a measure of $f_{\rho'}$. Should our results be confirmed without the need of further additional terms, from eq. (5) and $\sigma_{tot}(m_{\rho'}^2) \simeq 4.4\cdot 10^{-32}\ \text{cm}^2$ we would get the ratio $f_{\rho'}^2/f_\rho^2 \approx 5$.

We emphasize also that an improvement on the experimental situation concerning the η and η' decays would lead to a better determination of the couplings f and f' and therefore of our theoretical predictions.

Let us finally note that according to our scheme the SU_3 partners of the ρ', such as ω', could at least in principle contribute to the e^+e^- annihilation cross-sections. Since no experimental information is up to now available, we have completely disregarded this kind of contributions.

A more detailed and wide analysis on the argument is actually in progress.

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