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The Reaction $e^+e^- \to \eta'(X^0)\gamma$ and the New Vector Mesons

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Abstract

The generalized vector meson dominance theory of Sakurai is used to study the production of η' mesons in electron–positron collisions. The differential and total cross sections are calculated, especially taking into account contributions from the new vector mesons $\rho'(1250)$ and $\rho''(1600)$. The influence of an SU(3) symmetry-breaking parameter β on the numerical results is also investigated

Introduction

The several successes as well as failures of the vector meson dominance (VMD) hypothesis are by now well known. The essence of VMD (Sakurai 1960, 1971) can be summarized by the following statement: the entire hadronic electromagnetic current $[j_\mu(x)]$ is identical with a linear combination of the known neutral vector meson fields $[\rho_\mu^0(x), \omega_\mu(x), \phi_\mu(x)]$, that is,

$$j_\mu(x) = -e\{(m_\rho^2/2\gamma_\rho)\rho_\mu^0(x) + (m_\omega^2/2\gamma_\omega)\omega_\mu(x) + (m_\phi^2/2\gamma_\phi)\phi_\mu(x)\}, \qquad (1)$$

where m_V ($V = \rho, \omega, \phi$) denotes the vector-meson mass and γ_V is a measure of the γ–V coupling strength:

$$em_V^2/2\gamma_V \equiv (\alpha\pi)^{\frac{1}{2}} m_V^2/\gamma_V; \qquad (2)$$

here α is the fine structure constant ($=1/137$). This conjecture has greatly stimulated the study of photon–hadron interactions and has proved to be a useful guide in explaining many of the observed phenomena. Nevertheless, there are difficulties with the theory. For example, according to VMD the Compton amplitude T is related to the transverse vector meson photoproduction amplitudes T_{tr} by

$$T(\gamma p \to \gamma p) = \sum_{V=\rho,\omega,\phi} \{(\alpha\pi)^{\frac{1}{2}}/\gamma_V\}\, T_{\mathrm{tr}}(\gamma p \to V^0 p). \qquad (3)$$

However, if the values of the interaction constants γ_V are taken from the experimental determinations at Orsay and Novosibirsk, it is found that the ρ, ω and ϕ mesons in equation (3) contribute only to about 78% of the Compton amplitude. Difficulties with the VMD interpretation are also encountered in other areas of photoproduction and in the study of electromagnetic form factors (Schildknecht 1969). One of these difficulties is attributed to the ambiguity in choosing the frames of reference.

The missing 22% contribution in equation (3) above has presented the theorists with a challenging problem. One explanation put forward is that we are finally starting to see the effects of parton scattering not dominated by the ρ meson (cf. the four-point diagrams of Brodsky *et al.* 1972). Another possibility has been proposed by Sakurai (1972): that the missing 22% is simply due to the presence of higher mass vector states coupled to the photon. In fact, there is some experimental evidence for the existence of two new vector mesons, namely $\rho'(1250)$ and $\rho''(1600)$ (Bacci *et al.* 1972; Barbarino *et al.* 1972; Conversi *et al.* 1974; Alles-Borelli *et al.* 1975). Also the possibility of there being vector mesons heavier than the well-established ρ, ω and ϕ mesons has been predicted by the Veneziano and Regge pole models (Veneziano 1968; Shapiro 1969; Barger and Cline 1969). If the higher mass vector mesons do exist and if they decay into $\pi\pi$ (Johnson *et al.* 1976), $\pi\pi\pi$ or $\mathrm{K\bar{K}}$ modes, then, in the case when they retain the s-channel helicity of the photon, we would expect certain decay correlations similar to those observed for ρ, ω and ϕ. Higher mass vector mesons could, of course, also decay into other final states.

Wolf (1972) has considered the effect on the VMD model of including a contribution from the $\rho''(1600)$ meson alone, and has evaluated the sum rule for amplitudes in equation (3) at $9{\cdot}3$ GeV/c. He obtained

$$\begin{aligned} \underset{(\gamma\mathrm{p}\to\gamma\mathrm{p})}{0{\cdot}87\pm0{\cdot}02} &= \underset{(\gamma\mathrm{p}\to\rho\mathrm{p})}{0{\cdot}52\pm0{\cdot}04} + \underset{(\gamma\mathrm{p}\to\omega\mathrm{p})}{0{\cdot}066\pm0{\cdot}014} + \underset{(\gamma\mathrm{p}\to\phi\mathrm{p})}{0{\cdot}043\pm0{\cdot}004} + \underset{(\gamma\mathrm{p}\to\rho''\mathrm{p})}{0{\cdot}08\pm0{\cdot}03} \\ &= 0{\cdot}71\pm0{\cdot}09\,. \end{aligned} \tag{4}$$

The ρ'' contribution clearly reduces the gap between the left- and right-hand sides of the sum rule, but further contributions from high mass vector mesons are required to satisfy equation (3).

It is the aim of the present paper to consider the reaction

$$\mathrm{e}^+\mathrm{e}^- \to \eta'(X^0)\gamma \tag{5}$$

in the framework of a generalized vector meson dominance (GVMD) model. Here η' is taken to be the ninth member of the pseudoscalar nonet with quantum numbers $J^{PC} = 0^{-+}$ and mass $\mu_{\eta'} = 958$ MeV. We exclude the possibility of the E(1420) meson being the ninth member. In addition to the ρ, ω and ϕ mesons we include the two new vector mesons $\rho'(1250)$ and $\rho''(1600)$. These new mesons can be the first and second daughters respectively of the ρ meson in the Veneziano spectrum, the ρ'' mass being close to the g-meson mass (1680 MeV). In our calculations, the relevant coupling strengths are determined using the quark model with the presently known decay rates.

In all calculations similar to the present ones it has been found to be necessary to amend the original GVMD scheme in order to obtain quantitative agreement with the experimental results. One generally adopted improvement has been to incorporate the effects of breaking of SU(3) symmetry. This amounts to the inclusion of corrections for ω–ϕ and η–η' mixing (Baracca and Bramon 1967, 1970; Cremmer 1969) and the use of chiral symmetries (Alles 1970; Gounaris 1970*a*, 1970*b*). In view of this we have introduced here a symmetry-breaking parameter β in the $g_{V\eta'\gamma}$ ($V = \rho, \omega, \phi$) coupling constant. The effect on the cross sections for different values of this parameter is also studied.

Cross Section Formulae

In what follows we assume that the principal mechanism for the reaction $e^+e^- \to \eta'\gamma$ is governed by the $\gamma \to V$ transition followed by the $V \to \eta'\gamma$ decay (Fig. 1). Let p_1, p_2, k, k' and q be the four-momenta of the electron, positron, photons (real and virtual) and η' meson respectively. Then, to the lowest order in α, the matrix element M for the reaction has the form

$$M = (e/k'^2)\, F(V)\, \bar{v}(-p_2)\, \gamma_\mu u(p_1)\, \varepsilon^{\mu\nu\tau\sigma} k'_\nu k_\tau A_\sigma \bar{\phi}(q)\,, \tag{6}$$

where

$$F(V) = \sum_{V=\rho,\omega,\phi,\rho',\rho''} \left(-\frac{em_V^2}{g_V}\right) \frac{g_{V\eta'\gamma}}{k'^2 - m_V^2 + \mathrm{i}\Gamma_V m_V}\,, \tag{7}$$

$g_V = 2\gamma_V$, $g_{V\eta'\gamma}$ is the interaction constant at the vertex of η' with V and γ, m_V is the mass of the vector meson V with width Γ_V, and A_σ is the photon polarization vector.

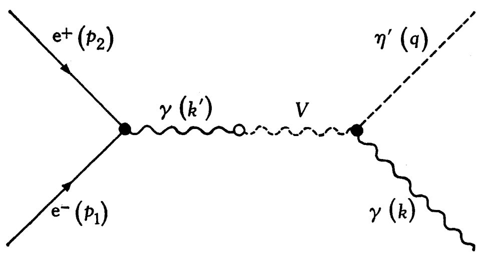

Fig. 1. Feynman diagram for electron–positron annihilation into an η' meson and a photon via a virtual photon and an intermediate vector meson.

Table 1. Interaction constants used in calculations

Vector meson V	Mass[A] m_V (MeV)	Width[A] Γ_V (MeV)	Coupling constants $g_V^2/4\pi$	$g_{V\eta'\gamma}$
ρ	770	150	$2\cdot1\pm0\cdot11$[B]	$0\cdot06360$
ω	780	10	$14\cdot8\pm2\cdot80$[B]	$-0\cdot02121$
ϕ	1020	4	$11\cdot0\pm1\cdot60$[B]	$-0\cdot04242$
ρ'	1250	150	7[C]	$0\cdot04154$[E]; $0\cdot05872$[F]
ρ''	1600	350	16[D]	$0\cdot01735$[E]; $0\cdot02452$[F]

[A] Values from Particle Data Group (1974). [B] Augustin (1969). [C] Conversi *et al.* (1974). [D] Wolf (1972). [E] Assuming linear η–η' mixing. [F] Assuming quadratic η–η' mixing.

From equation (6) the expression for the differential cross section can be obtained as

$$\mathrm{d}\sigma/\mathrm{d}\Omega = (\alpha/128\pi)\,|F(V)|^2 \{1-(\mu_{\eta'}/2E)^2\}^3 (1+x^2)\,, \tag{8}$$

where $\mu_{\eta'}$ is the mass of the η' meson, $x = \cos\theta$ with θ the angle between the three-dimensional momenta of the electron and the η' meson, and $2E = \sqrt{s}$ with E the beam energy. A straightforward integration of equation (8) gives

$$\sigma = \tfrac{1}{24}\alpha\,|F(V)|^2 \{1-(\mu_{\eta'}/2E)^2\}^3\,. \tag{9}$$

Interaction Constants

The interaction constants used in the calculations are summarized in Table 1. For the $g_{V\eta'\gamma}$ vertex, since there are as yet no experimental data available for $V \to \eta'\gamma$ decay widths we have used the quark model (Bramon and Greco 1974), which leads to the results

$$g_{\rho\pi^0\gamma} = -\tfrac{1}{3}g_{\omega\pi^0\gamma} \equiv g/3\,, \qquad g_{\rho\eta\gamma} = -g_{\rho\eta'\gamma} = g/\surd 2\,,$$
$$g_{\omega\eta\gamma} = g_{\omega\eta'\gamma} = g/3\surd 2\,, \qquad g_{\phi\eta\gamma} = g_{\phi\eta'\gamma} = \surd 2\, g/3\,.$$

Taking the experimental value of the $\omega \to \pi^0\gamma$ decay width ($\approx 0\cdot 9$ MeV) and using the width formula

$$\Gamma(V \to P\gamma) = g_{VP\gamma}^2(m_V^2 - m_P^2)^3/96\,\pi m_V^3\,, \tag{10}$$

where P indicates a pseudoscalar meson, we obtain $g_{\omega\pi^0\gamma} \approx 0\cdot 09$, which then leads to the values of $g_{\rho\eta'\gamma}$, $g_{\omega\eta'\gamma}$ and $g_{\phi\eta'\gamma}$ given in the last column of Table 1.

Assuming the existence of the new vector meson nonets V' ($\rho', \omega', \phi', \mathrm{K}^{*\prime}$) and V'' ($\rho'', \omega'', \phi'', \mathrm{K}^{*\prime\prime}$), Renard (1974) has recently calculated some of the decay widths of the members of these nonets. Under a hypothesis of linear η–η' mixing he obtains

$$\Gamma(\rho' \to \eta'\gamma) = 0\cdot 04 \text{ MeV}, \qquad \Gamma(\rho'' \to \eta'\gamma) = 0\cdot 06 \text{ MeV}, \tag{11a}$$

from which follow the values for $g_{\rho'\eta'\gamma}$ and $g_{\rho''\eta'\gamma}$ of $0\cdot 04154$ and $0\cdot 01735$ shown in Table 1. Similarly the values for quadratic η–η' mixing are obtained from the results

$$\Gamma(\rho' \to \eta'\gamma) = 0\cdot 08 \text{ MeV}, \qquad \Gamma(\rho'' \to \eta'\gamma) = 0\cdot 11 \text{ MeV}. \tag{11b}$$

In an alternative approach to the computation of the coupling strengths using the effective Lagrangian with SU(3) octet breaking, the expressions for the $g_{V\eta'\gamma}$ ($V = \rho, \omega, \phi$) take the form (Singer 1970)

$$g_{\rho\eta'\gamma} = \frac{2he}{g}\frac{1+\beta}{K_\rho^{\frac{1}{2}}}\,, \qquad g_{\omega\eta'\gamma} = \frac{2he}{g}\frac{(1-\beta)\sin\theta}{(3K_\omega)^{\frac{1}{2}}}\,, \qquad g_{\phi\eta'\gamma} = -\frac{2he}{g}\frac{(1-\beta)\cos\theta}{(3K_\phi)^{\frac{1}{2}}}\,, \tag{12}$$

where $K_V = m^2/m_V^2$ with $m = 847$ MeV, $\theta = 27\cdot 5°$, β is a symmetry-breaking parameter and the quantities g and h are given by

$$g^2/4\pi = 3\cdot 35\,, \qquad h^2/4\pi = 0\cdot 03192\,. \tag{13}$$

In this effective Lagrangian model the results for the coupling constants (12) are somewhat controlled by the choice of the parameter β. In a similar analysis of photoproduction of η' mesons, Matinian and Shakhnazarian (1971) found β values of $-0\cdot 7$, $-0\cdot 5$ and $-0\cdot 3$ to give reasonable results, and these values have been adopted here.

Results

With the set of parameters given in the preceding section we have calculated the differential and total cross sections for the process (5), and the results are presented graphically in Figs 2 and 3.

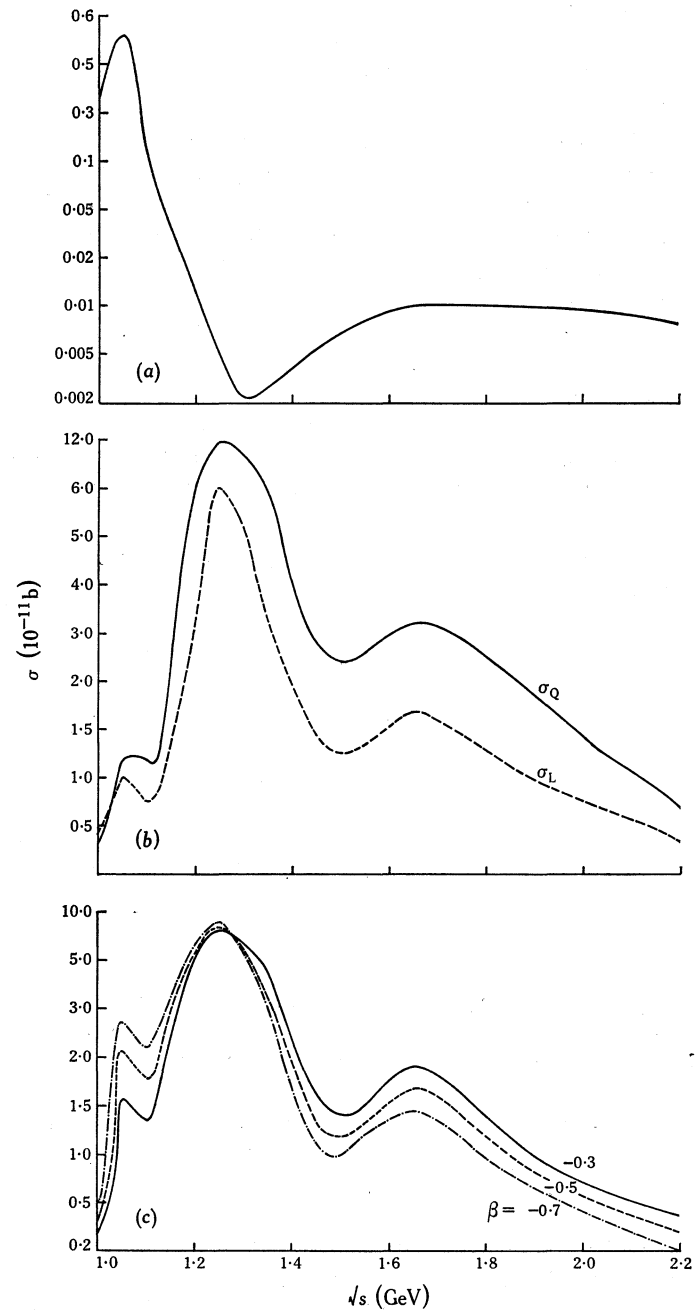

Fig. 2. Total cross sections σ in the reaction $e^+e^- \to \eta'\gamma$, as a function of the energy parameter $\sqrt{s}$, for: (*a*) contributions from ρ, ω, and ϕ mesons only; (*b*) inclusion of contributions from ρ' and ρ'' mesons, with both linear (σ_L) and quadratic (σ_Q) mixing of η and η'; (*c*) the three indicated values of the symmetry-breaking parameter β. (Note that nonlinear condensed scales for σ have been employed for convenience here.)

Fig. 2*a* gives the total cross section σ as a function of the energy parameter $\sqrt{s}$, taking into account only contributions from the vector mesons ρ, ω and ϕ. In this case σ remains almost constant between about 1·6 and 2 GeV and then begins to gradually decrease. The production of the ϕ mesons is clearly indicated by a peak very near threshold (≈ 1 GeV).

Fig. 2*b* gives the total cross sections for linear (σ_L) and quadratic (σ_Q) mixing of η and η', including contributions from all five mesons ρ, ω, ϕ, ρ' and ρ''. Near threshold the σ_L value is above that for σ_Q, but the curves cross at about 1·03 GeV and thereafter σ_L is always less than σ_Q. The production of the ρ' and ρ'' mesons is shown by distinct peaks. It is clear that the inclusion of these new mesons considerably enhances the cross section.

Fig. 2*c* shows the cross section corresponding to the three values $-0\cdot3$, $-0\cdot5$ and $-0\cdot7$ of the symmetry-breaking parameter β. It is interesting to note that the curve for $\beta = -0\cdot3$ starts from the lowest point but after generating two peaks becomes the upper value and tends to maintain a relative position with respect to the curve for $\beta = -0\cdot7$, which has opposite behaviour. The $-0\cdot5$ curve, however, takes a middle course throughout. All three curves are seen to intersect at an energy $\sqrt{s}$ of about 1·275 GeV.

The angular distributions corresponding to energy values equivalent to the ρ'' and ρ' masses are given in Fig. 3.

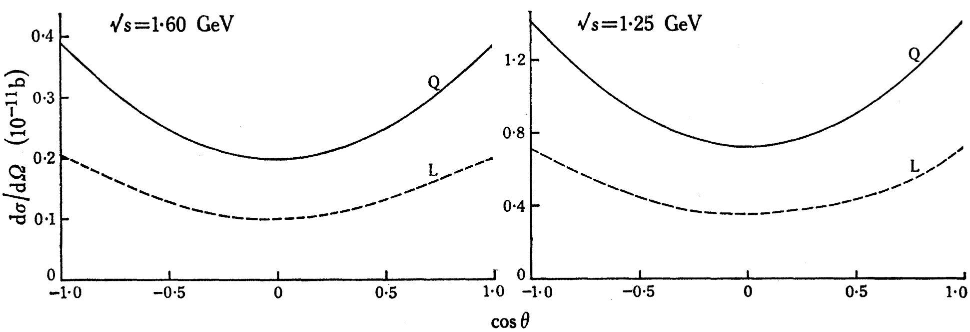

Fig. 3. Angular distributions for the reaction $e^+e^- \to \eta'\gamma$ corresponding to values of the energy parameter $\sqrt{s}$ equivalent to the masses of the ρ'' and ρ' mesons, namely 1·60 and 1·25 GeV respectively. The curves for linear (L) and quadratic (Q) mixing of η and η' are indicated.

Shui-Yin Lo (1966) has previously calculated cross sections for the reactions

$$e^+e^- \to PP, PV, VV, P\gamma,$$

not including the new ρ' and ρ'' mesons. Comparison of his results with the above calculations shows that the cross sections for $e^+e^- \to \eta'\gamma$ are extremely small relative to those for $e^+e^- \to \pi^0\gamma$ (Cremmer and Gourdin 1969). The present calculations, which are based on a GVMD approach, focus attention on the possible role of the proposed new vector mesons ρ' and ρ'' in electron–positron reactions. In principle we could have also chosen to consider contributions from other vector mesons ω', ω'', ϕ' and ϕ'', but there is little evidence as yet for the existence of these mesons. There have been several recent attempts to study similar reactions with colliding beams (Bacci *et al.* 1975; B. Stella, personal communication), and we hope that the present calculations will, in addition to providing a crucial test of the GVMD model, assist in the interpretation of the results of such experiments.

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