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F E Close and G J Gounaris

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Rutherford Appleton Laboratory Chilton DIDCOT Oxfordshire OX11 0QX

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Searching for Exotic Mesons in e^+e^- annihilation at $DA\Phi NE$ †

F.E. Close
Rutherford Appleton Laboratory,
Chilton, Didcot, Oxon, OX11 OQX, England,

and

G.J. Gounaris
Department of Theoretical Physics, University of Thessaloniki,
Gr-54006, Thessaloniki, Greece.

Abstract

$DA\Phi NE$ should be useful for testing the nature of the vector mesons directly produced in e^-e^+ annihilation, as well as the nature of the $C = +$ states produced in the radiative decays of these vector mesons. In the $DA\Phi NE$ energy range, these latter states may have spin up to two and any parity. Provided the background can be handled and the spin of the produced state is known, the study of the angular distributions in these decays can measure the parity of the produced meson as well as the ratios of the independent production helicity amplitudes. These ratios provide sensitive tests for quark model classification of the states, in particular the enigmatic $f_1(1420)$. Thus, they can be used to indicate whether the mesons involved are consistent with the usual $q\bar{q}$ interpretation, or whether other interpretations like *e.g.* hybrid, glueball or multiquark, are more favorable for some of them.

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The $DA\Phi NE$ [1] ϕ factory will eventually access electron positron annihilation at energies above the $\phi(1020)$ mass, reaching to 1.5 or even possibly 2 GeV in the c.m. This will enable the study of the dynamical nature of mesons lying in a mass region that is central to the quest for gluonic hadrons [2], as well as enabling the test of radical ideas on the nature of confinement [3,4,5,6]. Thus, we may be able to identify the conventional $q\bar{q}$ mesons in the 1-2 Gev region, and to investigate the nature of certain controversial or unconventional states that do not appear to fit naturally in the quark model description of hadrons [2,7].

The most direct application of $DA\Phi NE$ is in the production of vector mesons in e^-e^+ annihilation. Its primary role is, of course, to concentrate on the $\phi(1020)$, but $DA\Phi NE$ may also help to clarify the existence and couplings of peculiar states like $\omega_x(1100,\ \Gamma = 30 \pm 24)$ [8], $\rho_x(1266,\ \Gamma = 110 \pm 35)$ [9], $\omega(1440)$ and $\rho(1460)$ which have been claimed before[1][10,2,11].

The I=0,1 vector mesons $\omega(1440)$, $\omega(1600)$, $\rho(1460)$ and $\rho(1700)$, have found their way to the PDG list [2] and should be considered to some extent as (containing at least) true resonances. The latest analysis of their properties is given in [11]. In the past, they have been most simply interpreted as $^3S_1$ and $^3D_1$ quarkonia states [12], however, more recent analyses by Clegg Donnachie and Kalashnikova [11,13] conclude that this interpretation is probably inadequate. One possibility for a consistent description of the vector mesons in the 1.2 to 1.7 GeV range arises if $q\bar{q}$-glue hybrids are being manifested, of which $\omega(1440)$ and $\rho(1460)$ are specific examples [13]. An alternative picture is that one does without hybrids, but allows for mixing with $qq\bar{q}\bar{q}$ states. In this latter case one requires further $qq\bar{q}\bar{q}$ states, both ρ and ω-like, which are relatively low lying [13]. Donnachie, Clegg and Kalashnikova [14] argue that the controversial $\rho_x(1266)$ and $\omega_x(1100)$ mentioned above, may be such states. Thus, their existence is pivotal in discriminating between the hybrid and the $qq\bar{q}\bar{q}$ picture. Specifically, in the hybrid picture theses states have no place whereas they may be accommodated in the $qq\bar{q}\bar{q}$ interpretation. Important experiments attempting at clarifying their existence could therefore be possible at $DA\Phi NE$.

The state $\omega_x(1100)$ was once claimed to have been seen in Bethe-Heitler interference [8]. The mass of this state was found to be $1097 \pm 19\ MeV$, while its total and electronic widths are given as $\Gamma = 30 \pm 24\ MeV$ and $\Gamma(e^-e^+) = 50 - 100eV$. From this we would conclude that in the absence of any other contributions at the peak of the resonance

$$\delta R = \sigma(e^-e^+ \to hadrons)/\sigma(e^-e^+ \to \mu^+\mu^-) = 0.6 \pm 0.4 \quad . \tag{1}$$

This is 1% of the ϕ signal and may be separable from the ϕ with good statistics and resolution. Hence a careful study on the high mass side of the $\phi(1020)$ can decide whether $\omega_x(1100)$ and/or $\rho_x(1266)$ really exist.

$DA\Phi NE$ may also be used to study the nature of $C = +$ states. The most fruitful way to do so is by measuring at the peak of $\rho(1460)$, whose mass is most recently

[1]For the masses of the latter two states we follow the findings in [11].

determined to be $1.463 \pm 0.025\ GeV$, while the electronic and hadronic widths are $\Gamma(e^-e^+) = 1.6 - 3.4\ keV$ and $\Gamma_{tot} = 311 \pm 62 MeV$ [11]. These results imply an increase of the e^-e^+ annihilation cross section at its peak corresponding to

$$\delta R = \sigma(e^-e^+ \to \rho(1460) \to hadrons)/\sigma(e^-e^+ \to \mu^+\mu^-) \sim 1.3 \quad . \tag{2}$$

With a luminosity of $10^{32} cm^{-2} s^{-1}$, some months of running at the higher energies at $DA\Phi NE$ will enable the study of radiative decays of vector mesons like *e.g.* $\rho(1460)$ into $C = +$ states. Several of these states, having spin up to two and either parity, are particularly interesting.To motivate our more detailed discussion we present first some illustrative examples.

The easiest interpretation of these measurements arises if $\rho(1460)$ is a ${}^3S_1$ quarkonium state, (as expected in the Godfrey and Isgur picture of the quark model spectrum [15]), which could be tested by looking at its radiative decay to the well established ${}^3P_{2,1}$ states $f_2(1270)$, $a_2(1320)$, $f_1(1285)$ and $a_1(1260)$. In such a case the independent helicity amplitudes satisfy certain constraints (to be discussed later, see eqs (16) and (23)): if any of these relations is violated then we would conclude that $\rho(1460)$ is not simply an ordinary ${}^3S_1$ quarkonium. Further useful knowledge may be subsequently acquired by searching for the $\rho(1460)$ radiative decay to the controversial $f_2(1430)$, which has been claimed in J/Ψ radiative decays, (see p.1486 in ref.[2]) and compare the ratios of its various helicity production amplitudes to those for the well established ${}^3P_2$ quarkonium state $f_2(1270)$ [2]. The interpretation of this latter measurement would of course depend on whether the previously mentioned measurement supports the quarkonium assignment of $\rho(1460)$.

As another notable example we could measure the single amplitude determining the production of the 0^{++} states $f_0(975)$ or $a_0(980)$. This way we can test whether these mesons are the ${}^3P_0$ analogs of the well established ${}^3P_2$ quarkonium state $f_2(1270)$, or whether one of them at least is exotic [4,5,6]. The peculiarities of the 1^{++} sector can also be studied at DAΦNE. The interest here stems from the fact that the PDG list already includes ten axial mesons in this region, not all of which can be quarkonia. The odd one out appears to be the $f_1(1420)$. This state has also been seen in $\gamma - \gamma^*$ and may be a KK^* molecule or even a 1^{++} hybrid state [16,17]. There exist also some questions concerning its parity so that the quark model exotic $J^{PC} = 1^{-+}$ is not fully excluded [2].

In the present paper, we consider ways of elucidating this possibility by looking at the exclusive production of such states in the radiative decays of $\rho(1460)$ or in the e^-e^+ continuum. We always assume that we know the spin J of the produced state and that we somehow understand the background. These processes enable us to measure the ratios of the helicity amplitudes determining the production of these states, and thereby test their parity. Moreover, since the quark model makes unambiguous predictions for these ratios, very strong constraints on possible deviations from the quarkonium-like structure could be imposed.

The radiative decay for

$$e^- e^+ \to 1^{--} \to J^{P+} \; \gamma \quad , \tag{3}$$

(where J^{P+} denotes any $C = +$ state with $P = \pm$), is described by

$$\frac{d\sigma(e^-e^+ \to 1^{--} \to J^{P+}\gamma)}{d\cos\theta} = \sum_{m_1=\pm 1} \sum_{\lambda_1\lambda_2} \left[d^1_{m1,\lambda_1-\lambda_2}(\theta) \; |\langle \lambda_1\lambda_2|T^1(0)|m_1\rangle| \right]^2 \quad . \tag{4}$$

Here m_1 measures the projection of the spin of the initial 1^{--} state along the e^- beam taken as the z axis in the e^-e^+ c.m. frame. Its only allowed values are $m_1 = \pm 1$. The production angle of the J^{P+} state with respect the same e^- axis is denoted by θ, while λ_1 and λ_2 describe the helicities of the J^{P+} state and the photon respectively. The various partial wave helicity amplitudes for the radiative decay, (to lowest order in α), of the initially formed 1^{--} state, are given by $\langle \lambda_1\lambda_2|T^1(0)|m_1\rangle$, where the argument of T^1 emphasizes that the final photon in process (3) is on its mass shell; *i.e.* the photon momentum k_μ satisfies $k^2 = 0$. These amplitudes depend on the dynamics responsible for the existence of the initial 1^{--} and the final J^{P+} states. For $J \geq 1$, where more than one amplitude contributes, the θ distribution is determined by the ratios of these amplitudes and provides therefore a strong test of the quark model.

More information on these ratios may be obtained by looking also at the emission of a virtual photon decaying to a l^-l^+ pair in a process such as

$$e^-e^+ \to 1^{--} \to J^P \; \gamma^* \to J^{P+} \; (l^-l^+) \quad . \tag{5}$$

Now the final state distribution depends also on the angle φ, defined as the angle between the J^{P+} production plane and the decay plane of $\gamma^* \to l^-l^+$. By definition $0 \leq \varphi \leq \pi/2$. The final state distribution depends also on the angle θ and on the squared momentum k^2 of γ^* (where $k^2 > 4m_l^2$) such that

$$\frac{d\sigma(e^-e^+ \to 1^{--} \to J^{P+}\gamma^* \to J^{P+}(l^-l^+))}{dk^2 d\cos\theta d\varphi} = \frac{\alpha}{16\pi^2}\frac{1}{k^4}\left(1 - \frac{4m_l^2}{k^2}\right)^{1/2}$$

$$\cdot \sum_{m_1=\pm 1} \sum_{\lambda_1\lambda_2\lambda_2'} d^1_{m1,\lambda_1-\lambda_2}(\theta) d^1_{m1,\lambda_1-\lambda_2'}(\theta) L_{\lambda_2'\lambda_2} \langle \lambda_1\lambda_2|T^1(k^2)|m_1\rangle \langle \lambda_1\lambda_2'|T^1(k^2)|m_1\rangle^* \quad , \tag{6}$$

where again λ_1 is the J^{P+} helicity, λ_2 or λ_2' denote the helicity of γ^*, and $L_{\lambda_2'\lambda_2}$ is the γ^* density matrix. Denoting by m_l the mass of the final leptons and integrating out the l^- polar angle in the γ^* decay plane, we find

$$L_{\lambda_2'\lambda_2} = \frac{8}{3} \begin{pmatrix} k^2 + 2m_l^2 & 0 & \frac{1}{2}(k^2 - 4m_l^2)\exp i2\varphi \\ 0 & k^2 + 2m_l^2 & 0 \\ \frac{1}{2}(k^2 - 4m_l^2)\exp -i2\varphi & 0 & k^2 + 2m_l^2 \end{pmatrix} \quad , \tag{7}$$

where the rows and columns correspond to γ^* helicities $+1, 0, -1$. Of course, process (5) is suppressed with respect to (3) by an extra power of α and it is useful only so far as the φ distribution is needed.

Since in *DAΦNE* k^2 cannot be very large, γ^* is very close to its mass shell and behaves almost like a real photon. Therefore we can neglect all amplitudes involving a longitudinal γ^*, and conclude therefore that the same kind of helicity amplitudes, involving only transverse photons, contribute in both (3,4) and (5,6). After integrating over φ in (6,7), $L_{\lambda_2'\lambda_2}$ becomes essentially the unit matrix, which means that the θ distribution for on and off-shell photons is given by the same expression in terms of the helicity amplitudes; compare (4, 6). Parity and time inversion invariance for such amplitudes imply respectively

$$\langle\lambda_1\lambda_2|T^1(k^2)|m_1\rangle = P(-1)^J\langle-\lambda_1 \; -\lambda_2|T^1(k^2)|m_1\rangle \quad , \tag{8}$$

$$\langle\lambda_1\lambda_2|T^1(k^2)|m_1\rangle = -\langle\lambda_1\lambda_2|T^1(k^2)|-m_1\rangle^* \quad . \tag{9}$$

In the following we apply (4, 6, 8, 9) to the production of resonances with specific spin J and parity $P = \pm 1$.

J=0 States. We start from the radiative production of a $J = 0$ state with parity P, for which there is only one independent helicity amplitude taken to be

$$\mathcal{A}(k^2) = \langle\lambda_2 = + \,|T^1(k^2)|m_1 = +\,\rangle \quad . \tag{10}$$

This leads to

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta)|\mathcal{A}(0)|^2 \quad , \tag{11}$$

for process (3) and

$$\frac{d\sigma}{dk^2 d\varphi} \sim \frac{\alpha}{k^2}\left(1-\frac{4m_l^2}{k^2}\right)^{1/2} |\mathcal{A}(k^2)|^2\left\{\left(1+\frac{2m_l^2}{k^2}\right)+\frac{P}{4}\left(1-\frac{4m_l^2}{k^2}\right)\cos(2\varphi)\right\} \quad , \tag{12}$$

for (5). Eq (12) indicates that the sign of the $\cos(2\varphi)$ coefficient discriminates between the two different parities ($P = \pm$) of the produced $J = 0$ state; thus for example the $\cos(2\varphi)$ coefficient for $f_0(975)$ and $a_0(980)$ should be opposite to those of η and $\eta'(960)$ [18]; as we will see below it is also true for higher spin resonances. The overall production rate of 0^{++} mesons is described by an E1 transition and therefore is described by one amplitude only. Thus in the quark model the production of the $^3P_0$ quarkonium state is fully determined by the radiative production of the well established $^3P_2$ quarkonia $f_2(1270)$ and $a_2(1320)$; see below[19,21]. Therefore, means of testing whether $f_0(975)$ or $a_0(980)$ are the $^3P_0$ analogs of the well established $^3P_2$ $f_2(1270)$, $a_2(1320)$ are supplied. The same process may also be used to study the quark content of the candidates for radially excited 0^{-+} states namely $\pi(1300)$, $\eta(1295)$ [2] and $\eta(1400)$ claimed by MARK III in the $K\bar{K}\pi$ and $\eta\pi\pi$ modes [22].

J=1 States. We next consider the $J = 1$ case. This has the extra interest that a quarkonium structure for the final state meson is only possible in the 1^{++} configuration, and not the 1^{-+} one. Parity and time inversion invariance imply that there exist only two independent amplitudes which we take to be

$$\mathcal{B}_1(k^2) = \langle ++|T^1(k^2)|+\rangle \quad , \quad \mathcal{B}_0(k^2) = \langle 0+|T^1(k^2)|+\rangle \quad . \tag{13}$$

Substituting in (4,6), using (8,9), we get

$$\frac{d\sigma}{d\cos\theta} \sim (2|\mathcal{B}_1(0)|^2 + |\mathcal{B}_0(0)|^2)\left[1 + \frac{(|\mathcal{B}_0|^2 - 2|\mathcal{B}_1|^2)}{(2|\mathcal{B}_1(0)|^2 + |\mathcal{B}_0(0)|^2)}\cos^2(\theta)\right] \quad , \tag{14}$$

for process (3) and

$$\frac{d\sigma}{dk^2 d\varphi} \sim \frac{\alpha}{k^2}\left(1 - \frac{4m_l^2}{k^2}\right)^{1/2}\left\{\left(1 + \frac{2m_l^2}{k^2}\right)(|\mathcal{B}_1(k^2)|^2 + |\mathcal{B}_0(k^2)|^2) - \right.$$

$$\left. -\frac{P}{4}|\mathcal{B}_0(k^2)|^2\left(1 - \frac{4m_l^2}{k^2}\right)\cos(2\varphi)\right\} \quad , \tag{15}$$

for (5). We note in (15) that the sign of the $\cos(2\varphi)$ coefficient determines again the parity of the produced state. **Thus, provided $J = 1$ for the produced state is established, a positive sign for the $cos(2\phi)$ term will be an unambiguous signature that an exotic 1^{-+} state is formed.** Taking into account the fact that the ${}^3P_1$ 1^{++} nonet is already complete and that $f_1(1420)$ appears as a tenth state, it will be very interesting to use (15) in order to measure its parity and discriminate between a vector or axial vector assignment [2,16]. The fact that $f_1(1420)$ has already been seen in $\gamma\gamma^*$ fusion argues in favor of the feasibility of such a search [16].

Leaving this aside, we now consider the production of an 1^{++} state through process (3). According to the quark model, if this state is a ${}^3P_1$ quarkonium and the initial decaying one is an ordinary ${}^3S_1$ $q\bar{q}$ vector meson, then the amplitudes are determined mainly by E1 and M2 transitions which, in an obvious notation, imply [19,20]

$$\mathcal{B}_1(0) = \sqrt{3}\left(E + \frac{M}{2}\right) \quad , \quad \mathcal{B}_0(0) = \sqrt{3}\left(E - \frac{M}{2}\right) \quad , \tag{16}$$

for real photons in the final state; (compare (13)). Let us now specialize to the case that the initial e^-e^+ energy is around the $\rho(1460)$ mass, and that we are interested in studying the structure of a state in the $f_1(1420)$ region. In such a case the momentum of the outgoing photon is about 40 MeV, which, according to the quark model implies strong E1 dominance and $\mathcal{B}_1/\mathcal{B}_0 \sim 1$. For such a case (14) gives $d\sigma/\cos\theta \sim [1 - \cos^2(\theta)/3]$ [19,21]. For process (5) on the other hand, where k^2 is non-vanishing, the ratio $\mathcal{B}_1(k^2)/\mathcal{B}_0(k^2)$ will grow dramatically with k^2 [23]. Such a rise has already been seen in baryons and has important implications for the spin dependent electroproduction [24]. In the

DAΦNE kinematical region however, the final γ^* is only slightly off shell, implying again $\mathcal{B}_1(k^2)/\mathcal{B}_0(k^2) \simeq 1$ and a small M/E value.

Thus, the basic quark model prediction which can be tested through (14) and (15), is that the production of a true $^3P_1$ 1^{++} quarkonium state through radiative decay of a $^3S_1$ $q\bar{q}$ vector meson, is characterized by $\mathcal{B}_1/\mathcal{B}_0 \simeq 1$ in the DAΦNE kinematical region. This prediction is quite strong and safe. The main problem is background. If this is overcome and the 1^{++} quantum numbers of the produced state are established, we can conclude that any indication from (14-16) implying that $|M/E|$ is large and thus $\mathcal{B}_1/\mathcal{B}_0$ very different from +1, would either mean that the initial state is $^3D_1$ (which is hard to imagine in this mass region, see ref [15]), or that at least one of the participating mesons is exotic [19,21,23].

J=2 States. As a final example, we consider the production of a 2^{P+} state through process (3) and (5). The number of independent amplitudes after parity and time inversion invariance is taken into account, become now three. For these amplitudes we take

$$\mathcal{C}_2(k^2) = \langle 2\ 1|T^1(k^2)|+\rangle \ , \ \mathcal{C}_1(k^2) = \langle 1\ 1|T^1(k^2)|+\rangle \ , \ \mathcal{C}_0(k^2) = \langle 0\ 1|T^1(k^2)|+\rangle \ . \tag{17}$$

Substituting in (4,6), using (8,9) we get in this case

$$\frac{d\sigma}{d\cos\theta} \sim (|\mathcal{C}_0(0)|^2 + |\mathcal{C}_2(0)|^2 + 2|\mathcal{C}_1(0)|^2)[1 + \mathcal{R}_\theta \cos^2(\theta)] \quad , \tag{18}$$

with

$$\mathcal{R}_\theta = \frac{(|\mathcal{C}_0(0)|^2 + |\mathcal{C}_2(0)|^2 - 2|\mathcal{C}_1(0)|^2)}{(|\mathcal{C}_0(0)|^2 + |\mathcal{C}_2(0)|^2 + 2|\mathcal{C}_1(0)|^2)} \tag{19}$$

for process (3), and

$$\frac{d\sigma}{dk^2 d\varphi} \sim \frac{\alpha}{k^2}\left(1 - \frac{4m_l^2}{k^2}\right)^{1/2} (|\mathcal{C}_0(k^2)|^2 + |\mathcal{C}_1(k^2)|^2 + |\mathcal{C}_2(k^2)|^2)\left\{\left(1 + \frac{2m_l^2}{k^2}\right) + P\mathcal{R}_\varphi\left(1 - \frac{4m_l^2}{k^2}\right)\cos(2\varphi)\right\} \quad , \tag{20}$$

with

$$\mathcal{R}_\varphi = \frac{|\mathcal{C}_0|^2}{4(|\mathcal{C}_0(k^2)|^2 + |\mathcal{C}_1(k^2)|^2 + |\mathcal{C}_2(k^2)|^2)} \tag{21}$$

for (5). Again the sign of the $\cos(2\varphi)$ distribution determines the parity of the produced 2^{P+} state. The results (19, 21) imply also

$$-1 \leq \mathcal{R}_\theta \leq 1 \quad , \quad 0 \leq \mathcal{R}_\varphi \leq \frac{1}{4} \quad , \tag{22}$$

as a consequence of parity and time inversion invariance and the approximation to neglect amplitudes involving longitudinal γ^* in the DAΦNE kinematical region for process (5).

In the remaining we restrict to the production of a 2^{++} which may be more interesting for DAΦNE. If this state happens to be a quarkonium $^3P_2$, then standard quark model considerations imply [19,21]

$$\mathcal{C}_0 = E - \frac{3M}{2} \quad , \quad \mathcal{C}_1 = \sqrt{3}\left(E - \frac{M}{2}\right) \quad , \quad \mathcal{C}_2 = \sqrt{6}\left(E - \frac{M}{2}\right) \quad , \tag{23}$$

where the k^2 dependence is suppressed. Combining (23) with (19) and (21) we get

$$-\frac{3}{11} \leq \mathcal{R}_\theta \leq 1 \quad , \quad 0 \leq \mathcal{R}_\varphi \leq \frac{3}{20} \quad , \tag{24}$$

which should be satisfied if the produced state is a $^3P_2$ quarkonium. This quarkonium prediction can be made even more restrictive if E1 dominance for the amplitudes in (23) is taken into account, which gives

$$\mathcal{R}_\theta = \frac{1}{13} \quad , \quad \mathcal{R}_\varphi = \frac{1}{40} \quad . \tag{25}$$

Provided that the production of a 2^{++} state is established, any violation of (24) will be a proof that an exotic 2^{++} state has been identified. The same conclusion could also be drawn if a sufficiently strong violation of (25) is observed , implying an unacceptably large value for M/E.

Apart from a comment in the discussion after (12), up to now we have not used the less general quark model predictions relating the amplitudes for producing $P = C = +$ mesons with different J. If such relations are used, then connections between the $\mathcal{A}$, $\mathcal{B}_i$ and $\mathcal{C}_j$ amplitudes are found. These connections stem from the E1 dominance found in the quark model for the $\mathcal{B}_i$ and $\mathcal{C}_j$ amplitudes, which combined with the fact that the $\mathcal{A}$ amplitude for the 0^{++} production is purely E1 induced, leads to (modulo phase space effects)

$$\sigma(e^-e^+ \to V \to \gamma(E1) + {}^3P_{0,1,2}) = 1:3:5 \quad . \tag{26}$$

These relations may be used to verify the tacit assumption that the axial meson $f_1(1285)$ is the $^3P_1$ quarkonium partner of the established $^3P_2$ $f_2(1270)$, and to explore the nature of $f_1(1420)$. Furthermore, we can also study whether either of $f_0(975)$ and $a_0(980)$ is a conventional $^3P_0$ quarkonium partner of $f_2(1270)$, or whether they have some other dynamical structure. The $f_0(975)$ is particularly interesting in this regard. According to (26), if it is the $^3P_0$ partner of $f_2(1270)$, its production strength is fixed. Conversely, if different production rates are seen, it may be possible to deduce whether $f_0(975)$ is a "small" (e.g. [4]) or "large" (e.g. [5]) system; since the E1 transition amplitude is in proportion to $(\Sigma_i e_i r_i)$, where e_i and r_i are the charge and vector displacement of the charged constituents (see [6]).

We have shown in the present paper that provided the background can be handled, the radiative production of $C = +$ states in e^-e^+ annihilation at DAΦNE can be very helpful in indicating whether the mesons involved are consistent with the usual

$q\bar{q}$ interpretation, or whether other interpretations such as *e.g.* hybrid, glueball or multiquark, are more favorable for some of them.

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