Abstract

The suggestion of momentum dependence in the amplitude for rho-omega mixing has generated concern over related implications for vector meson dominance and the photon-rho coupling. We discuss two established representations of vector meson dominance and show that one of these is completely consistent with such a coupling. We then apply it to a calculation of the pion electromagnetic form-factor. Our analysis leads to a new value for the on-shell rho-omega mixing amplitude of $-3800 \pm 370$ MeV$^2$.

E-mail: hoconnel, bpearce, athomas, awilliam@physics.adelaide.edu.au
1 Introduction

It was recently suggested that the $\rho - \omega$ mixing amplitude, $\Pi_{\rho\omega}$, might vary fairly rapidly with the invariant mass-squared of the meson near $q^2 = 0$ [1]. Since then there has been a significant amount of work on the problem, [2, 3, 4, 5, 6], culminating in the suggestion that under certain reasonable conditions $\Pi_{\rho\omega}$ should actually vanish at $q^2 = 0$ [7]. As we will show explicitly, this behaviour presents no difficulty with regard to our understanding of the mixing amplitude at the $\omega$ pole, through the interference of the decay $\omega \to \pi\pi$ with $\rho \to \pi\pi$ [8, 9]. However, it has profound implications for the modelling of charge symmetry violation (CSV) in the nucleon–nucleon (NN) force [10, 11, 12]. Indeed the variation found in Refs. [1, 2, 3, 4, 5, 6, 7] dramatically reduces the conventional CSV NN potentials obtained under the usual assumption that $\Pi_{\rho\omega}$ is a constant [1, 13].

Although there is no rigorous derivation of the coupling of the photon to the $\rho$ in QCD, if it occurs through the same sort of quark loop used in Refs. [1, 2, 3, 4] to model $\rho - \omega$ mixing one would expect that it too should vanish at $q^2 = 0$. This is in contrast with the most commonly used version of vector meson dominance (VMD) where the $\gamma - \rho$ coupling is fixed (see below). As discussed by Miller [14], it is not obvious that one can reconcile a $\gamma - \rho$ mixing amplitude that vanishes at $q^2 = 0$ with the success of VMD in describing data such as the pion form-factor measured in $e^+e^- \to \pi^+\pi^-$. Clearly the resolution of this issue is essential to our understanding of CSV.

Our purpose here is to show that one can fit the measured pion form-factor with a $\gamma - \rho$ coupling that vanishes at $q^2 = 0$. We begin by recalling that there are actually two related representations of VMD. We shall see that the one less frequently used, described by Sakurai in the 1960’s, is indeed consistent with this vanishing coupling and reproduces the form-factor very nicely. In the process of fitting the data, we extract a new value of the $\rho - \omega$ mixing amplitude at the $\omega$ pole, $\Pi_{\rho\omega}(m^2_\omega)$.

2 Vector Meson Dominance

To examine $\rho - \omega$ mixing in any detail requires an understanding of the model used to describe the process. Our available data on $\rho - \omega$ mixing is almost exclusively obtained from the electromagnetic (EM) pion form-factor. Like almost all low energy photon-hadron interactions [15] the EM form-factor is modelled by VMD [16], which we shall now discuss.

VMD assumes that the dominant role in the interaction of the photon with hadronic matter is played by vector mesons. It is an attempt to model non-perturbative interactions determined by QCD, which, cannot yet be evaluated in this low-energy regime. The traditional representation of VMD (which, following the conventions of our recent review [1], we shall refer to as VMD2) assumes that the photon couples to hadronic matter exclusively through a vector meson, to which it couples with a fixed strength proportional to the mass squared of the meson.
For the photon–rho–pion system, the relevant part of the VMD2 Lagrangian is
\[
\mathcal{L}_{\text{VMD2}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} \rho_{\mu\nu} \rho^{\mu\nu} + \frac{1}{2} m_{\rho}^2 \rho_{\mu}^2 - g_{\rho\pi\pi} J_\rho^\mu - \frac{e m_{\rho}^2}{g_{\rho}} \rho_{\mu} A_\mu + \frac{1}{2} \left( \frac{e}{g_{\rho}} \right)^2 m_{\rho}^2 A_\mu A^\mu, \tag{1}
\]
where \( J_\rho^\mu \) is the pion current, \((\vec{\pi} \times \partial_\mu \vec{\pi})_3\), and \( F_{\mu\nu} \) and \( \rho_{\mu\nu} \) are the EM and \( \rho \) field strength tensors (here \( e \equiv |e| \)). From Eq. (1) one arrives at a pion form-factor of the form \[9\]
\[
F_\pi(q^2) = -\frac{m_{\rho}^2}{q^2 - m_{\rho}^2 + i m_{\rho} \Gamma_\rho(q^2)} \frac{g_{\rho\pi\pi}}{g_{\rho}}, \tag{2}
\]
where conventionally one takes \[17, 18\]
\[
\Gamma_\rho(q^2) = \Gamma_\rho \left( \frac{q^2 - 4 m_{\pi}^2}{m_{\rho}^2 - 4 m_{\pi}^2} \right)^{3/2} \frac{m_{\rho}}{\sqrt{q^2}} \theta(q^2 - 4 m_{\pi}^2). \tag{3}
\]
This VMD2 Lagrangian, rederived by Bando et al. \[19\] from a model based on hidden local gauge symmetry, has some unappealing features. Firstly, the \( \rho - \gamma \) interaction is supposed to be modelling the quark-polarisation of the photon, which necessarily vanishes at \( q^2 = 0 \) to preserve EM gauge invariance \[20\], whereas the coupling determined by Eq. (1) is fixed. Hence the VMD2 dressing of the photon propagator shifts the pole away from zero, and thus a bare photon mass must be introduced into the Lagrangian to counterbalance this and ensure that the dressed photon is massless. Secondly, recent studies \[21, 22\] have shown that the best fit to \( e^+ e^- \to \pi^+ \pi^- \) requires a non-resonant term (i.e., a contribution in which the \( \rho \) does not appear), which VMD2 lacks. Thirdly, the constraint
\[
F_\pi(0) = 1, \tag{4}
\]
which reflects the fact that the photon sees only the charge of the pion at zero momentum transfer, is only realised by Eq. (3) in the limit of universality \( g_\rho = g_{\rho\pi\pi} \), which is seen to be only approximate in nature \[23\].

For these reasons we prefer the alternative formulation \[16\] which we shall call VMD1 \[4\], with the following Lagrangian
\[
\mathcal{L}_{\text{VMD1}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} \rho_{\mu\nu} \rho^{\mu\nu} + \frac{1}{2} m_{\rho}^2 \rho_{\mu}^2 - g_{\rho\pi\pi} J_\rho^\mu - e A_\mu J_\pi^\mu = \frac{e}{2 g_{\rho}} F_{\mu\nu} \rho^{\mu\nu}. \tag{5}
\]
The key features of this representation are the absence of a photon mass term and the presence of a term \( F_{\mu\nu} \rho^{\mu\nu} \), which produces a momentum-dependent \( \gamma - \rho \) coupling of the form \[4\],
\[
\mathcal{L}_{\gamma\rho} = -\frac{e}{2 g_{\rho}} F_{\mu\nu} \rho^{\mu\nu} \rightarrow -\frac{e}{g_{\rho}} q^2 A_\mu \rho^\mu. \tag{6}
\]
This, of course, decouples the photon from the $\rho$ at $q^2 = 0$, hence keeping the photon massless in a natural way. However, the photon is still able to couple to the hadronic current through the direct coupling $-eA_\mu J_\pi^\mu$, giving us a non-resonant term. We now have a form-factor of the form [8]

$$F_\pi(q^2) = 1 - \frac{q^2 g_{\rho\pi\pi}}{g_\rho[q^2 - m_\rho^2 + im_\rho \Gamma_\rho(q^2)]}. \quad (7)$$

We note that Eq. (7) automatically satisfies the requirement for the form-factor given in Eq. (4).

We illustrate the difference between the two representations in Fig. 1.

![Diagram](image)

Figure 1: Contributions to the pion form-factor in the two representations of vector meson dominance a) VMD1 b) VMD2.

3 $\rho-\omega$ mixing

At present the widely quoted value of for $\Pi_{\rho\omega} \equiv \Pi_{\rho\omega}(m_\omega^2)$ [11], is obtained from the branching ratio formula for the $\omega$

$$B(\omega \rightarrow \pi\pi) = \frac{\Gamma(\omega \rightarrow \pi\pi)}{\Gamma(\omega)}, \quad (8)$$

derived from a $\rho-\omega$ mixing analysis where

$$\Gamma(\omega \rightarrow \pi\pi) = \left| \frac{\Pi_{\rho\omega}}{im_\rho \Gamma_\rho} \right|^2 \Gamma(\rho \rightarrow \pi\pi). \quad (9)$$

Using the branching ratio determined in 1985 by the Novosibirsk group [17]

$$B(\omega \rightarrow \pi\pi) = (2.3 \pm 0.4 \pm 0.2)\% \quad (10)$$
Coon and Barrett obtained $\Pi_{\rho\omega} = -4520 \pm 600 \text{MeV}^2$. We aim to extract $\Pi_{\rho\omega}$ from a fit to the cross-section of the reaction $e^+e^- \to \pi^+\pi^-$ using

$$\sigma(q^2) = \frac{\alpha^2\pi}{3} \frac{(q^2 - 4m^2\rho)^{3/2}}{s^{5/2}} |F_\pi(q^2)|^2,$$

and the form-factor determined by VMD1 (Eq. (1)).

So far, we have not introduced any effects of charge symmetry violation (CSV) into our system, and hence the $\omega$ (which cannot otherwise couple to a $\pi^+\pi^-$ state) does not appear. In their recent examination of the EM pion and nucleon form-factors using VMD1, Dönges et al.\cite{18} introduced the $\omega$ through a covariant derivative in the pion kinetic term. This produces a direct contribution from $\omega \to 2\pi$ without any $\rho-\omega$ mixing, but does not provide a good representation of data in the resonance region. We shall use the mixed propagator\cite{7}, where the mixing is introduced by an off-diagonal piece, $\Pi_{\rho\omega}$ in the vector meson self-energy. To first order in CSV [i.e., to $O(\Pi_{\rho\omega})$], the propagator is given by (we ignore pieces proportional to $q\mu$ as we couple to conserved currents)

$$D_{\mu\nu} = \left( \begin{array}{cc} 1/s_\rho & \Pi_{\rho\omega}/s_\rho s_\omega \\ \Pi_{\rho\omega}/s_\rho s_\omega & 1/s_\omega \end{array} \right) g_{\mu\nu},$$

(12)

where

$$s_\rho \equiv q^2 - \Pi_{\rho\rho}(q^2) - m^2_\rho,$$

$$\equiv q^2 - m^2_\rho + i m_\rho \Gamma_\rho(q^2),$$

(13)

(14)

and similarly for the $\omega$. We can now examine how to use this propagator to model a system with CSV\cite{3}. Note that as the pion form-factor is only sensitive to $\rho-\omega$ mixing near the $\omega$ pole we can ignore the momentum dependence of the meson mixing and treat $\Pi_{\rho\omega}$ as a constant.

In a matrix notation, the Feynman amplitude for the process $\gamma \to \pi\pi$, proceeding via vector mesons, can be written in the form

$$iM_{\gamma \to \pi\pi} = \begin{pmatrix} iM_{\rho\rho \to \pi\pi} & iM_{\omega\omega \to \pi\pi} \\ iM_{\rho\omega \to \pi\pi} & iM_{\omega\rho \to \pi\pi} \end{pmatrix} \begin{pmatrix} iD_{\mu\nu} & \end{pmatrix} \begin{pmatrix} iM_{\gamma \to \rho\rho} & iM_{\gamma \to \omega\omega} \end{pmatrix},$$

(15)

where the matrix $D_{\nu\mu}$ is given by Eq. (12) and the other Feynman amplitudes are derived from $\mathcal{L}_{\text{VMD1}}$. If we make the standard assumption that the pure isospin state $\omega_I$ does not couple to two pions ($\mathcal{M}_{\omega\omega \to \pi\pi} = 0$) then to lowest order in the mixing, Eq. (13) is just

$$M_{\gamma \to \pi\pi} = \begin{pmatrix} M_{\rho\rho \to \pi\pi} & 0 \\ M_{\rho\omega \to \pi\pi} & M_{\omega\rho \to \pi\pi} \end{pmatrix} \begin{pmatrix} \frac{1}{s_\rho} & \Pi_{\rho\omega}/s_\rho s_\omega \\ \Pi_{\rho\omega}/s_\rho s_\omega & 1/s_\omega \end{pmatrix} \begin{pmatrix} M_{\gamma \to \rho\rho} & M_{\gamma \to \omega\omega} \end{pmatrix}. $$

(16)

Expanding this just gives

$$M_{\gamma \to \pi\pi} = M_{\rho\rho \to \pi\pi} \frac{1}{s_\rho} M_{\gamma \to \rho\rho} + M_{\rho\omega \to \pi\pi} \frac{1}{s_\rho} \Pi_{\rho\omega} M_{\gamma \to \omega\omega},$$

(17)
which we recognise as the sum of the two diagrams shown in Fig. 2.

The couplings that enter this expression, through $M_{\rho I \to \pi \pi}$, $M_{\gamma \to \rho I}$ and $M_{\gamma \to \omega I}$, always involve the unphysical pure isospin states $\rho_I$ and $\omega_I$. However, we can re-express Eq. (17) in terms of the physical states by first diagonalising the vector meson propagator. We can, at this point, introduce a diagonalising matrix \[ C = \begin{pmatrix} 1 & \epsilon \\ -\epsilon & 1 \end{pmatrix} \] (18)

where, to lowest order in the mixing,

\[ \epsilon = \frac{\Pi_{\rho \omega}}{s_\rho - s_\omega}. \] (19)

We now insert identities into Eq. (16) and obtain

\[
M_{\gamma \to \pi \pi}^\mu = \begin{pmatrix} M_{\rho I \to \pi \pi}^\mu & 0 \end{pmatrix} C C^{-1} \begin{pmatrix} 1/s_\rho & \Pi_{\rho \omega}/s_\rho s_\omega \\ \Pi_{\rho \omega}/s_\rho s_\omega & 1/s_\omega \end{pmatrix} C C^{-1} \begin{pmatrix} M_{\gamma \to \rho I} \\ M_{\gamma \to \omega I} \end{pmatrix},
\]

(20)

where to first order in $\epsilon$ we have identified the physical amplitudes as

\[
M_{\rho \to \pi \pi}^\mu = M_{\rho I \to \pi \pi}^\mu, \tag{21}
\]

\[
M_{\omega \to \pi \pi}^\mu = \epsilon M_{\rho I \to \pi \pi}^\mu, \tag{22}
\]

\[
M_{\gamma \to \rho} = M_{\gamma \to \rho I} - \epsilon M_{\gamma \to \omega I}, \tag{23}
\]

\[
M_{\gamma \to \omega} = M_{\gamma \to \omega I} + \epsilon M_{\gamma \to \rho I}. \tag{24}
\]
Expanding Eq. (20), we find

$$\mathcal{M}_{\gamma\rightarrow\pi\pi} = \mathcal{M}_{\rho\rightarrow\pi\rho}^\mu \frac{1}{s_{\rho}} \mathcal{M}_{\gamma\rightarrow\rho} + \mathcal{M}_{\omega\rightarrow\pi\omega}^\mu \frac{1}{s_{\omega}} \mathcal{M}_{\gamma\rightarrow\omega}$$

$$= \mathcal{M}_{\rho\rightarrow\pi\rho}^\mu \frac{1}{s_{\rho}} \mathcal{M}_{\gamma\rightarrow\rho} + \mathcal{M}_{\rho\rightarrow\pi\omega}^\mu \frac{\Pi_{\rho\omega}}{s_{\rho} - s_{\omega}} \frac{1}{s_{\omega}} \mathcal{M}_{\gamma\rightarrow\omega},$$

which is the form usually seen in older works. At first glance there seems to be a slight discrepancy between Eqs. (17) and (25). The source of this is the definition used for the coupling of the vector meson to the photon. The first, Eq. (17), uses couplings to pure isospin states, the second, Eq. (25) uses "physical" couplings (i.e., couplings to the mass eigenstates) which introduce a leptonic contribution to the Orsay phase, as discussed by Coon et al. [8]. This phase is, however, rather small. If we assume $\mathcal{M}_{\gamma\rightarrow\rho I} = 3 \mathcal{M}_{\gamma\rightarrow\omega I}$ and define the leptonic phase $\theta$ by

$$\frac{\mathcal{M}_{\gamma\rightarrow\omega}}{\mathcal{M}_{\gamma\rightarrow\rho}} = \frac{1}{3} e^{i\theta}$$

then, to order $\epsilon$,

$$\tan \theta = \frac{10 \Pi_{\rho\omega}}{3m_{\rho} \Gamma_{\rho}}.$$  (27)

This gives $\theta = 5.7^\circ$ for $\Pi_{\rho\omega} = -4520\text{MeV}^2$, as obtained by Coon et al. [8]. This small leptonic contribution to the Orsay phase is the principal manifestation of diagonalising the $\rho-\omega$ propagator.

4 **Fit to $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ using VMD1**

We are now in a position to write down the CSV form-factor based on the VMD1 form-factor of Eq. (7) and the mixed state contribution of Eq. (25),

$$F_\pi(q^2) = 1 - \frac{q^2 g_{\rho\pi\pi}}{g_\rho [q^2 - m_{\rho}^2 + i m_{\rho} \Gamma_\rho(q^2)]} - \frac{q^2 \epsilon g_{\rho\pi\pi}}{g_\omega [q^2 - m_{\omega}^2 + i m_{\omega} \Gamma_\omega]}$$

(28)

where,

$$\epsilon = \frac{\Pi_{\rho\omega}}{s_{\rho} - s_{\omega}}$$

(29)

$$= \frac{\Pi_{\rho\omega}}{m_{\omega}^2 - m_{\rho}^2 - i (m_{\omega} \Gamma_\omega - m_{\rho} \Gamma_\rho(q^2))}.$$  (30)

The $\omega$ decay formula of Eq. (9) can now be seen to follow from Eq. (28) with an approximation (namely that $\Gamma_\omega$ is very small and that $m_{\rho}^2 = m_{\omega}^2$) for $\epsilon$. Because the width of the $\omega$ is very small we can safely neglect any momentum dependence in it, and simply
use $\Gamma_\omega(m_\omega^2)$ \cite{21}. In principle we should include a contribution in Eq. (28) from the leptonic phase (Eqs. (26) and (27)), but, as this is very small, we can also safely ignore it and assume all phase comes from $\epsilon$.

All parameters except $\Pi_{\rho\omega}$ are fixed by various data as discussed below. The results of fitting this remaining parameter to the data are shown in Fig. 3 with the resonance region shown in close-up in Fig. 4.

![Cross-section of $e^+e^- \rightarrow \pi^+\pi^-$ plotted as a function of the energy in the centre of mass. The experimental data is from Refs. [17,21].](image)

The mass and width of the $\omega$ are as given by the Particle Data Group (PDG) \cite{24}, $m_\omega = 781.94 \pm 0.12$ MeV and $\Gamma_\omega = 8.43 \pm 0.10$ MeV. There has recently been considerable interest in the value of the $\rho$ parameters, $m_\rho$ and $\Gamma_\rho$, with studies showing that the optimal values \cite{21,22} may differ slightly from those given by the PDG. The value of $\Pi_{\rho\omega}$ is not sensitive to the masses and widths, and we have obtained a good fit with $m_\rho = 772$ MeV and $\Gamma_\rho = 149$ MeV, which are close to the PDG values.

The values of the coupling constants are however quite important for an extraction of $\Pi_{\rho\omega}$. We obtain $g_\rho$ and $g_{\rho\pi\pi}$ from $\Gamma(\rho \rightarrow e^+e^-) \sim 6.8$ MeV and $\Gamma(\rho \rightarrow \pi\pi) \sim 149$ MeV

$g_{\rho\pi\pi}^2/4\pi \sim 2.9$, \hspace{1cm} (31)

$g_\rho^2/4\pi \sim 2.0$, \hspace{1cm} (32)

which show, for example, that universality is not strictly obeyed (as mentioned previously).
Historically the ratio $g_\omega / g_\rho$ was believed to be around $3 \ [25]$, a figure supported in a recent QCD-based analysis $[26]$. Empirically though, the ratio can be determined $[22]$ from leptonic partial rates $[24]$ giving

$$\frac{g_\omega}{g_\rho} = \sqrt{\frac{m_\omega \Gamma(\rho \rightarrow e^+e^-)}{m_\rho \Gamma(\omega \rightarrow e^+e^-)}} \quad (33)$$

$$= 3.5 \pm 0.18. \quad (34)$$

Using these parameters we obtain a best fit around the resonance region shown in Fig. 4 ($\chi^2/d.o.f. = 14.1/25$) with $\Pi_{\rho\omega} = -3800$. There are two principle sources of error in our value for $\Pi_{\rho\omega}$. The first is a statistical uncertainty of $310 \text{ MeV}^2$ for the fit to data, and the second, of approximately $200 \text{ MeV}^2$ is due to the error quoted in Eq. (34). Adding these in quadrature gives us a final value for the total mixing amplitude, to be compared with the value $-4520 \pm 600 \text{ MeV}^2$ obtained by Coon and Barrett $[10]$. We find

$$\Pi_{\rho\omega} = -3800 \pm 370 \text{ MeV}^2. \quad (35)$$
5 Conclusions

It is now clear that a momentum dependent $\gamma^* - \rho$ coupling, together with a direct coupling of the photon to hadronic matter, yields an entirely adequate model of the pion form-factor. In fact, this picture is basically suggested by attempts to examine the $\gamma^* - \rho$ coupling via a quark loop. Model calculations typically find that the loop is momentum-dependent, and vanishes at $q^2 = 0$ (unless gauge invariance is spoiled by form-factors, or something of this nature). However, coupling the photon to quarks in the loop implies that the photon must also couple to the quarks in hadronic matter, thus introducing a direct photon-hadron coupling (independent of the $\rho$-meson), and leads us to take VMD1 as the preferred representation of vector meson dominance. It should now be clear that the appropriate representation of vector meson dominance to be used in combination with mixing amplitudes that vanish at $q^2 = 0$ is VMD1. The use of VMD2 in this context is inconsistent. As long as one is clear on this point, there are no dire consequences for momentum dependence in $\rho-\omega$ mixing.

Acknowledgments

This work was supported by the Australian Research Council.

References

[1] T. Goldman, J.A. Henderson and A.W. Thomas, Few Body Systems 12, 123 (1992).
[2] G. Krein, A.W. Thomas and A.G. Williams, Phys. Lett. B 317, 293 (1993).
[3] K.L. Mitchell, P.C. Tandy, C.D. Roberts and R.T. Cahill, Phys. Lett. B 335, 282 (1994).
[4] J. Piekaraicz and A.G. Williams, Phys. Rev. C 47 R2462 (1993).
[5] T. Hatsuda, E.M. Henley, Th. Meissner and G. Krein, Phys. Rev. C 49, 452 (1994).
[6] R. Friedrich and H. Reinhardt, $\rho-\omega$ mixing and the pion electromagnetic form-factor in the Nambu–Jona-Lasinio Model, [hep-ph/9501333].
[7] H.B. O’Connell, B.C. Pearce, A.W. Thomas and A.G. Williams, Phys. Lett. B 336, 1 (1994).
[8] S.A. Coon, M.D. Scadron and P.C. Mc Namee, Nucl. Phys. A287, 381 (1977).
[9] H.B. O’Connell, B.C. Pearce, A.W. Thomas and A.G. Williams, hep-ph/9501251, submitted for publication in Trends in Particle and Nuclear Physics, ed. W-Y Pauchy Hwang (Plenum Press).

[10] S.A. Coon and R.C. Barrett, Phys. Rev. C 36, 2189 (1987).

[11] P.C. McNamee, M.D. Scadron and S.A. Coon, Nucl. Phys. A249, 483 (1975).

[12] G.A. Miller, A.W. Thomas and A.G. Williams, Phys. Rev. Lett. 56, 2567 (1986); A.G. Williams, A.W. Thomas and G.A. Miller, Phys. Rev. C 36, 1956 (1987).

[13] M.J. Iqbal and J.A. Niskanen, Phys. Lett. B 322, 7 (1994).

[14] G.A. Miller and W.T.H van Oers, nucl-th/9409013, Chapter for Symmetries and Fundamental Interactions in Nuclei, eds. E.M. Henley and W. Haxton (World Scientific).

[15] W. Weise, Phys. Rep. 13, 53 (1974).

[16] J.J. Sakurai, Currents and Mesons, University of Chicago Press (1969).

[17] L.M. Barkov et al., Nucl. Phys. B256 365 (1985).

[18] H.C. Dönges, M. Schäfer and U. Mosel, nucl-th/9407012, to appear in Phys. Rev C, Feb 1995.

[19] M. Bando et al. Phys. Rev. Lett. 54, 1215 (1985).

[20] C.D. Roberts, Electromagnetic Pion Form Factor and Neutral Pion Decay Width, hep-ph/9408233.

[21] D. Benaksas et al., Phys. Lett. 39B, 289 (1972).

[22] A. Bernicha, G. López Castro and J. Pestieau, Phys. Rev. D 50, 4454 (1994)

[23] T. Hakioglu and M.D. Scadron, Phys. Rev. D 43, 2439 (1991)

[24] Particle Data Group, Phys. Rev. D 50, 1173 (1994).

[25] A.S. Goldhaber, G.C. Fox and C. Quigg, Phys. Lett. 30B, 249 (1969).

[26] G. Dillon and G. Morpurgo, Zeit. Phys. C 46, 467 (1994).