Hadronic Gauge Coupling for $\rho' \to \rho\pi\pi$

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Abstract. A reasonable understanding of the smallness of the $\rho' \to \pi\pi$ to the $\rho' \to \rho\pi\pi$ branching ratio in the context of the quark-pair creation model (QPCM) is achieved. Our crucial hypothesis consists in assuming that the $\rho$ can be phenomenologically considered as a gauge particle which couples to the derivative $\rho'\pi\pi$ coupling through a gauge principle. This fixes unambiguously the $\rho' \to \rho\pi\pi$ amplitude.

I. Introduction

The $\rho'(1600)$ meson was originally observed in $e^+e^-$-annihilations [1, 2] and in photoproduction [1, 3] through its dominant $\pi^+\pi^-\pi^+\pi^-$ decay mode. In a more recent $e^+e^-$-experiment, with larger statistics [4], its mass and width have been accurately established to be

$$m_{\rho'} = 1.57 \pm 0.08 \text{ GeV}$$
$$\Gamma_{\rho'} = 0.51 \pm 0.08 \text{ GeV},$$ (1)

while in other recent experiments the decay modes $\rho' \to \pi^+\pi^-\pi^0\pi^0$ [5, 6], $\rho' \to \pi^+\pi^-\eta$ [5, 7], $\rho' \to \pi^+\pi^-\pi^0$ [8] and (possibly) $\rho' \to K^*K \to K\bar{K}\pi$ [9] have been identified. The most striking feature of these data is the suppression of the $\pi\pi$ decay mode or, equivalently, the smallness of the branching ratio [1, 10]

$$R_{\rho'} = \frac{\Gamma(\rho' \to \pi\pi)}{\Gamma(\rho' \to 4\pi)} \approx 0.18.$$ (2)

The isoscalar partners, $\omega'$ and $\phi'$, of the $\rho'(1600)$ meson have been intensively searched in both $e^+e^-$-annihilation and photoproduction experiments. The situation, however, is still very confusing. Indeed, while some $e^+e^-$ data [9, 11, 12] seem to show unambiguously the existence of a $\phi'$ meson with a mass around 1.66 GeV, a more recent photoproduction experiment [13] excludes the presence of such a state. Moreover, the $\phi$-like nature of this controversial resonance is quite uncertain since its copious decay modes into $\omega\pi\pi$ [12] and $3\pi$ [14] contradict the almost pure $s\bar{s}$ quark content of the state proposed in [9]. The only point of agreement among the different experiments observing one (or two) isoscalar resonance(s) in the 1.6-1.7 GeV region is its (their) relatively narrow total width(s), $\Gamma_{\omega'} \approx 100 \text{ MeV}$. But this is a rather mince information which can hardly compensate the above mentioned contradictory results. Accordingly, we will not take these results into account (except that $\Gamma_{\omega'} < \Gamma_{\rho'}$) in our present approach to the $\rho'(1600)$ meson decay modes.

The suppression of the $\rho' \to \pi\pi$ decay has already been discussed by several authors [15, 18] in the context of a naive quark-pair creation model (QPCM) [19]. Here we will adhere to this successful approach to the problem but we will try to circumvent the difficulties one has to face (see below) when trying to account for the dominant $\rho' \to \rho\pi\pi \to 4\pi$ decay modes. This will be achieved assuming that the intermediate $\rho$-meson plays the role of a (massive) gauge particle [mediating à la Yang–Mills the SU(2)-isospin group] which couples to the $\rho'\pi\pi$ vertex through a gauge coupling. Some successful consequences of this assumption have already been discussed by the authors [20] in the context of the $\rho\pi\pi$ decay modes of the $f$- and $g$-mesons, and further tests of the same idea have been proposed more recently by Desmond and Lo [21]. Obviously, we do not claim that the $\rho$-meson is a genuine gauge
boson but simply that at the phenomenological level the universal \( \text{(à la Sakurai)} \) \( \rho \)-meson couplings to hadrons may be considered as originated by a gauge principle \[20\].

II. \( \rho' \to \pi \pi \) Decay

In the context of the QPCM \[19\] one assumes that the strong decay of a \( q \bar{q} \)-meson into two final mesons proceeds through the formation of a virtual \( q \bar{q} \)-pair with zero total momentum and with the vacuum quantum numbers \( J^{PC} = 0^+ + \), i.e. in the \( 3P_0 \)-state. Next, the initial (spectator) \( q \bar{q} \)-pair and the virtual one recombine into two \( q \bar{q} \)-pairs giving rise to the two final mesons with momentum conservation at each step. This introduces the well-known \[15, 19\] modulating factor—which depends on the final momentum and the nature of the three mesonsmultiplying a universal constant corresponding to the vacuum-\( q \bar{q} \) coupling. In our case one simply has \[15\].

\[
g_{\rho'\pi\pi} = g_{\rho\pi\pi} \left[ \frac{m_{\rho'}}{m_\rho} \right]^{3/2} \frac{3}{2} \frac{1}{9} \left[ 1 - \frac{2}{15} k_x^2 R^2 \right] \cdot \exp \left[ \frac{(k_x - k'_x)^2}{R^2} \right],
\]

where \( k_x (k'_x) \) is the pion momentum in the \( \rho \to \pi \pi \rho' \to \pi \pi \) decay and \( R \) is related to the radius (or equivalently, to the strength) of the three-dimensioanl harmonic oscillator whose wave functions describe the \( \pi, \rho \) and \( \rho' \) \( q \bar{q} \)-states. In (3) and in what follows we have further assumed that the \( \rho' \) corresponds to the first radial excitation of the \( \rho (770) \). Similarly, one can observe that the universal constant accounting for the \( q \bar{q} \) pair creation has disappeared when performing the ratio (3) and that there is one single parameter, \( R \), to be fixed.

Unfortunately we can only present rough estimates of the oscillator parameter \( R \). First, one can deduce from the well-known charge radius of the pion \[22\], \( \langle r^2 \rangle_{\text{em}} = 0.46 \text{ fm}^2 \), \( R^2 \approx 2 \langle r^2 \rangle_{\text{em}} / 3 \approx 8 \text{ GeV}^{-2} \). Secondly, from the van Royen-Weisskopf \[23\] formula and the experimental data \[1\] on \( \rho^0, \omega \) and \( \phi \) decay widths into lepton pairs one obtains \( R^2 \approx 8, 8 \) and \( 6 \text{ GeV}^{-2} \), respectively [from the \( \rho' \to e^+ e^- \) width and assuming (see below) that the \( \rho' \to \pi^+ \pi^- \pi^+ \pi^- \) branching ratio is 60\% one similarly obtains \( R^2 \approx 5 \text{ GeV}^{-2} \)]. Thirdly, from the level spacing in the \( \rho' \) (and other) spectra one can conclude \[24\] \( R^2 \approx 10 \text{ GeV}^{-2} \). All these estimates can be compared with those coming from other authors who have performed similar analysis: \( R^2 \approx 8 \text{ GeV}^{-2} \) \[15\], \( R^2 = 7 - 10 \text{ GeV}^{-2} \) (for \( \phi \)- and \( K^* \)-excitations, ref. 16) and \( R^2 = 4 - 20 \text{ GeV}^{-2} \) \[17\]. In spite of the rather large dispersion shown by these estimates of \( R^2 \) there seems to be a preferred range of values,

\[ R^2 = 8 - 10 \text{ GeV}^{-2}, \]

which we will adopt in what follows.

III. \( \rho' \to \rho \pi \pi \) Decays

The situation is more involved when trying to account for the large \( \rho' \to \rho \pi \pi \) decay width in the context of the QPCM \[15, 16\]. Indeed, this model applies exclusively to three-hadron vertices in such a way that one is led to consider the following possible decay chains

\[
\begin{align*}
\rho' &\to \rho \pi \pi \to p_\pi \pi \pi, \\
\rho' &\to A_1 \pi \pi \to p_\pi \pi \pi, \\
\rho' &\to \omega \pi \pi \to p_\pi \pi \pi,
\end{align*}
\]

(7a)

and

\[
\begin{align*}
\rho' &\to \rho \rho \to 4 \pi, \\
\rho' &\to \omega \pi \pi \to 4 \pi,
\end{align*}
\]

(7b)

where \( e (\sim 700) \) and \( A_1 (1100-1270) \) are two (rather ill defined \[1, 10\]) resonances with \( J^{PC} = 0^+ + \) and \( 1^+ - \), respectively. The first two decay chains, (7a), contribute to both the \( \rho' \to \rho \pi^+ \pi^- \pi^+ \pi^- \) and \( \rho' \to \rho^0 \pi^+ \pi^- \pi^0 \pi^0 \) decay modes, whereas the other two, (7b), can only lead to the \( \pi^+ \pi^- \pi^0 \pi^0 \) final state. Since the \( \rho' \to \pi^+ \pi^- \pi^+ \pi^- \) is the dominant and unambiguously established \( \rho' \) decay mode \[4\] one is forced to consider the decay chains quoted in (7a) (those given in (7b), on the other hand, have not been observed experimentally \[1, 5\]). The first chain, \( \rho e \), explains immediately the observed \( s \)-nature of the \( \pi \pi \)-pair proceeding from a scalar meson but—apart from the traditional difficulties (described in the mini-review of \[10\] encountered when dealing with this elusive \( e \)-meson—one cannot explain the smallness of the branching ratio \[10\] encountered when dealing with this elusive \( e \)-meson—one cannot explain the smallness of the branching ratio \( \Gamma (\rho' \to \rho \pi^+ \pi^- \pi^+ \pi^-) / \Gamma (\rho' \to \rho^0 \pi^+ \pi^- \pi^0) \). Indeed, a recent photoproduction experiment \[5\] gives an upper limit of 0.15 for that branching ratio, while it is predicted to be 1/2 if the \( e \) \( \pi \)-intermediate state is the dominant one (see also the