THE $\tau \to \nu\rho\pi$ DECAY AND A_1 MESON CHARACTERISTICS

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(Received June 7, 1979)

The $\tau \to \nu\rho\pi$ decay parameters are evaluated using the PCAC hypothesis and current algebraic methods. The angular and energy distributions are obtained. The polarization effects are discussed in detail. We showed that the D-wave contribution (in $A_1 \to \rho\pi$ decay) is suppressed.

1. Introduction

The existence of a new heavy lepton with a mass of 1.8 GeV [1] is now unambiguously proved. The observed cross section of the τ production in the e^+e^--annihilation, energy and angular distributions of the $e\mu$-events (e.g. the collinear angle distribution [2]) do not contradict the hypothesis that the τ lepton is pointlike with a spin of 1/2 [3].

A new type of neutrino with a mass of $m_\nu \leqslant 0.25$ GeV [4] appears obligatory in all decays of the τ lepton. Both the $V+A$ and $V-A$ couplings are acceptable, the latter being favoured [3].

In this note we investigate the $\tau \to \nu\varrho\pi$ decay which has already been observed [5, 6] with $B = (5\pm1.5)\%$ (according to the other data [4] $B = (10.4\pm2.4)\%$). This decay is determined by an axial part of a weak hadron current, hence the decay parameters may be evaluated using the PCAC hypothesis and current algebraic methods.

Owing to a comparatively large τ lepton mass one can investigate the behaviour of the axial $\pi\varrho$ form factors in a wide range of squared momentum transfer (from $(m_\pi+m_\rho)^2$ to $(m_\tau-m_\nu)^2$). The large τ lepton mass requires a consideration of all the three form factors.

Apart from the standard weak current which is transformed like ϱ and A_1 (or π) mesons one can imagine currents which have "wrong" G parity properties. The former are "first class" currents and the latter "second class". We evaluate the contribution of the second class current to different distributions of final particles.

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We also discuss in detail the polarization effects in the decay of the polarized τ lepton and evaluate the vector meson density matrix.

We emphasize that all the characteristics of the decay are very sensitive to the t-dependence of the form factors.

The investigation of the $\tau \to \nu\varrho\pi$ decay offers the unique chance to study the A_1 meson. The recent experimental data are not selfconsistent. The A_1 meson is usually generated in hadron-hadron interactions where the final state interaction, which distorts the spectrum of ϱ and π mesons, is essential. We have a pure $\varrho\pi$ system in $\tau \to \nu\varrho\pi$ decay which has (it is very important) A_1 quantum numbers ($J^P = 1^+$).

2. *The matrix element*

The matrix element of the $\tau \to \nu\varrho\pi$ decay is given by

$$M = \frac{G}{\sqrt{2}} \bar{u}(p_2)\gamma_\mu(1+\lambda\gamma_5)u(p_1)J_\mu,$$

$$J_\mu = [f_1(t)k_\mu + f_2(t)q_\mu]q \cdot U^* + f_3(t)U_\mu^* + if_4(t)\varepsilon_{\mu\nu\varrho\sigma}U_\nu^* k_\varrho q_\sigma, \tag{2.1}$$

where G is the Fermi coupling, λ is the g_A/g_V ratio, U — the polarization vector of the ϱ-meson, $t = (k+q)^2$ — the momentum transfer squared, f_1, f_2, f_3 are the form factors which correspond to the standard weak current, f_4 is the second class current form factor.

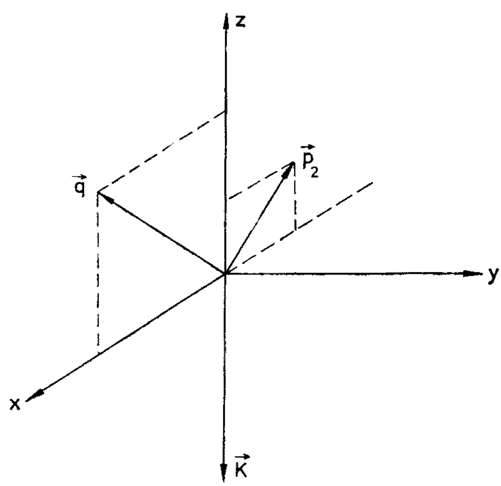

Fig. 1. The τ lepton rest frame

The form factors f_i ($i = 1-4$) are complex in the region of the timelike momentum transfer. Neglecting the second class current contribution one can obtain for the $|\overline{M}|^2$, after summing over the ϱ meson and ν_τ polarizations (in the lepton rest frame, see Fig. 1) the following formula

$$\overline{|M|^2} = G^2[(1+\lambda^2)(M_0 - S_y M_1) + m_\nu(1-\lambda^2)(M_2 + S_y M_1) - 2\lambda(S\cdot k M_3 + S\cdot q M_4)],$$

$$M_0 = \Phi_1(2k\cdot p_1 k\cdot p_2 - m_\varrho^2 p_1\cdot p_2) + \Phi_2(2q\cdot p_1 q\cdot p_2 - m_\pi^2 p_1\cdot p_2)$$

$$+\Phi_3(k\cdot p_1 q\cdot p_2 + k\cdot p_2 q\cdot p_1 - p_1\cdot p_2 k\cdot q) + 2p_1\cdot p_2|f_3|^2;$$

$$M_1 = 2q_x k_z \,\mathrm{Im}\left(Lf_1 f_2^* - f_1 f_3^* - \frac{q\cdot k}{m_\varrho^2} f_2 f_3^*\right);$$

$$M_2 = \Phi_1 m_\varrho^2 + \Phi_2 m_\pi^2 + \Phi_3 k\cdot q - 4|f_3|^2;$$

$$M_3 = \Phi_1(m_\varrho^2 + 2k\cdot p_2) + \Phi_2 m_\pi^2 + \Phi_3 q\cdot(k+p_2) - 2|f_3|^2;$$

$$M_4 = \Phi_1 m_\varrho^2 + \Phi_2(m_\pi^2 + 2q\cdot p_2) + \Phi_3 k\cdot(q+p_2) - 2|f_3|^2;$$

$$\Phi_1 = L|f_1|^2 + \frac{1}{m_\varrho^2}(2k\cdot q\,\mathrm{Re}\, f_1 f_3^* + |f_3|^2);$$

$$\Phi_2 = L|f_2|^2 - 2\,\mathrm{Re}\, f_2 f_3^*;$$

$$\Phi_3 = 2\,\mathrm{Re}\left(Lf_1 f_2^* - f_1 f_3^* + q\cdot k\frac{f_2 f_3^*}{m_\varrho^2}\right);$$

$$L = \frac{(k\cdot q)^2}{m_\varrho^2} - m_\pi^2;$$

we set $m_\tau = 1$ and S is the τ-lepton spin orientation vector.

The second class current contribution (we neglect the term proportional to $|f_4|^2$) is

$$\overline{|M^{(2)}|^2} = G^2\,\mathrm{Re}\,(f_3 f_4^*)\,[2\lambda(q\cdot p_2 k\cdot p_1 - q\cdot p_1 k\cdot p_2) + (1+\lambda^2)$$

$$\times(k\cdot p_2 S\cdot q - q\cdot p_2 S\cdot k) + m_\nu(1-\lambda^2)(q\cdot p_1 S\cdot k - S\cdot q k\cdot p_1)].$$

It is seen that $M_1 = 0$ when the relative phase of the form factors f_i $(i = 1, 2, 3)$ is zero.

It follows from Eq. (2.2) that there are the terms proportional to $(1-\lambda^2)$ when $m_\nu \neq 0$. This is a typical feature of the $(V+\lambda A)$ coupling.

The Dalitz plot (the hadron energy distribution) is given in the Appendix ($m_\nu = 0$, $m_\tau = 1$).

3. *Energy and angular distributions*

It is not difficult to obtain $dw/d\varepsilon$ where $\varepsilon = \varepsilon_\pi + \varepsilon_\varrho$ is the sum of π and ϱ meson energies, since the knowledge of the form factors $f_i(t)$ is unnecessary:

$$\frac{dw}{d\varepsilon d\Omega} = \frac{G^2 \Lambda^{1/2}(t, m_\pi^2, m_\varrho^2)}{768\pi^4 t}[(1-\varepsilon)^2 - m_\nu^2]^{1/2}\Big\{2(B_0 - B_1)[(1+\lambda^2)(\varepsilon-1) + 2m_\nu(1-\lambda^2)]$$

$$+\frac{1}{t}(4B_1-B_0)\left[(1+\lambda^2)(1-m_\nu^2-\varepsilon-\varepsilon m_\nu^2)+m_\nu(1-\lambda^2)(m_\nu^2+2\varepsilon-1)\right]$$

$$+2\lambda\vec{S}\cdot\vec{n}[(1-\varepsilon)^2-m_\nu^2]^{1/2}\left[2(B_0-B_1)+\frac{1}{t}(4B_1-B_0)(1-m_\nu^2)\right]\Bigg\},$$

$$B_0=\frac{1}{4m_\varrho^2}\Lambda(t,m_\pi^2,m_\varrho^2)\Bigg[m_\varrho^2|f_2|^2+m_\pi^2|f_3|^2+\mathrm{Re}\,(f_2f_3^*)(t-m_\pi^2-m_\varrho^2)$$

$$+2\,\mathrm{Re}\,f_3f_1^*-\frac{12m_\varrho^2|f_1|^2}{\Lambda(t,m_\pi^2,m_\varrho^2)}\Bigg].$$

$$B_1=\frac{1}{16m_\varrho^2t}\Lambda(t,m_\pi^2,m_\varrho^2)\,|f_2(t+m_\varrho^2-m_\pi^2)+f_3(t+m_\pi^2-m_\varrho^2)+2f_1|^2,$$

$$\Lambda(x,y,z)=(x-y-z)^2-4yz,\qquad t=m_\nu^2+2\varepsilon-1,\qquad \varepsilon=\varepsilon_\pi+\varepsilon_\varrho,$$

where $\vec{n}$ is the unit vector along the sum of π and ϱ meson momenta. We neglect here the second class current contribution.

The hadron energy distribution may be easily obtained in the rest frame of the other hadron and neutrino. Thus, the ϱ meson energy and angular distribution is given by (we set here $m_\nu=0$, $m_\tau=1$):

$$\frac{dw}{d\varepsilon_\varrho d\Omega_\varrho}=\frac{G^2|\vec{k}_\varrho|}{2^{11}\pi^4}\left(1+\frac{m_\pi^2}{2\varepsilon_\varrho-m_\varrho^2-1}\right)\int_{-1}^{+1}d\cos\theta^*\Bigg\{(1+\lambda^2)M_0$$

$$+2\lambda\vec{S}\cdot\vec{k}_\varrho\left[M_3+(q\cdot p_1\varepsilon_\varrho-q\cdot k)\frac{M_4}{|\vec{k}_\varrho|^2}\right]+8\lambda\,\mathrm{Re}\,(f_3f_4^*)(q\cdot p_2k\cdot p_1-q\cdot p_1k\cdot p_2)$$

$$+4(1+\lambda^2)\,\mathrm{Re}\,(f_3f_4^*)\vec{S}\cdot\vec{k}_\varrho\left(q\cdot p_2-k\cdot p_2\,\frac{q\cdot p_1\varepsilon_\varrho-q\cdot k}{|\vec{k}_\varrho|^2}\right)\Bigg\},$$

$$t=1+(\varepsilon_\varrho-1+|\vec{k}_\varrho|\cos\theta^*)\left(1+\frac{m_\pi^2}{2\varepsilon_\varrho-m_\varrho^2-1}\right),$$

$$k\cdot p_1=\varepsilon_\varrho,\qquad 2q\cdot p_1=1-2\varepsilon_\varrho+t,\qquad 2k\cdot q=t-m_\pi^2-m_\varrho^2,$$

where $\vec{K}_\rho$ is the meson momentum, θ^* is the π meson angle in the $\pi\nu_\tau$ rest frame.

The asymmetry of the ϱ meson angular distribution is

$$A_\varrho=\frac{dw(\theta=0)-dw(\theta=\pi)}{dw(\theta=0)+dw(\theta=\pi)}.$$

The analogous expressions for the π meson can be obtained in the same way.

The $\cos\theta_{\pi\rho}$ distribution may be written as

$$\frac{dw}{d\cos\theta_{\pi\varrho}} = \frac{G^2}{2^7\pi^3}\int\limits_{m_\varrho}^{\varepsilon_{\varrho\,\max}} d\varepsilon_\varrho \frac{|\vec{k}_\varrho|\,(1+m_\varrho^2-2\varepsilon_\varrho)}{(1-\varepsilon_\varrho+|\vec{k}_\varrho|\cos\theta_{\pi\varrho})}\,[(1+\lambda^2)M_0$$

$$+8\lambda\,\mathrm{Re}\,(f_3f_4^*)\,(q\cdot p_2k\cdot p_1-q\cdot p_1k\cdot p_2)],$$

where $\varepsilon_{\varrho\,\max} = \frac{1}{2}(1+m_\varrho^2)$, $m_\nu = 0$, $m_\tau = 1$.

4. *The form factors*

We have determined the $\tau\to\nu\varrho\pi$ form factors using the axial meson dominance (Fig. 2). The A_1 resonance description is favoured in this decay. Moreover the nonresonance background must be small because $w(\tau\to\nu A_1)/w(\tau\to\nu\varrho\pi)\cong 1$ [4]. In the considered approximation we obtain (ignoring the π meson pole contribution to f_1 and f_2)

$$f_1 = \frac{g_A}{m_A(t-m_A^2)}\left[g_1+\frac{1}{2}\,g_2\frac{m_A^2+m_\varrho^2-m_\pi^2}{m_A^2}\right],$$

$$f_2 = -\frac{g_2g_A}{m_A(t-m_A^2)},\quad f_3 = -\frac{g_1g_Am_A}{(t-m_A^2)}, \tag{4.1}$$

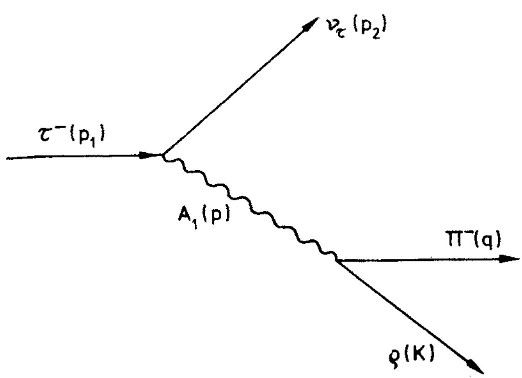

Fig. 2. The A_1-dominance model

where g_1 and g_2 are the $A_1\to\varrho\pi$ couplings. m_A^2 would be replaced by $m_A^2+im_A\Gamma_A$ because A_1 pole ($t=m_A^2$) lies in the physical region.

The experimental data for g_1 and g_2 couplings are not complete. That is why we evaluate the contributions to the energy distributions and the asymmetries which are proportional to g_1^2, g_1g_2 and g_2^2 separately. In Fig. 3 we plot the functions C_i and $A_\rho^{(i)}$ which are defined by

$$\frac{dw}{d\varepsilon_\varrho} = 10^{-13}\left(g_1^2 m_A^2 C_1 + \frac{g_1 g_2}{10} C_2 + \frac{g_2^2}{100 m_A^2} C_3\right),$$

$$A_\varrho = g_1 m_A^2 A_\varrho^{(1)} + g_1 g_2 A_\varrho^{(2)} + \frac{g_2^2}{m_A^2} A_\varrho^{(3)}. \tag{4.2}$$

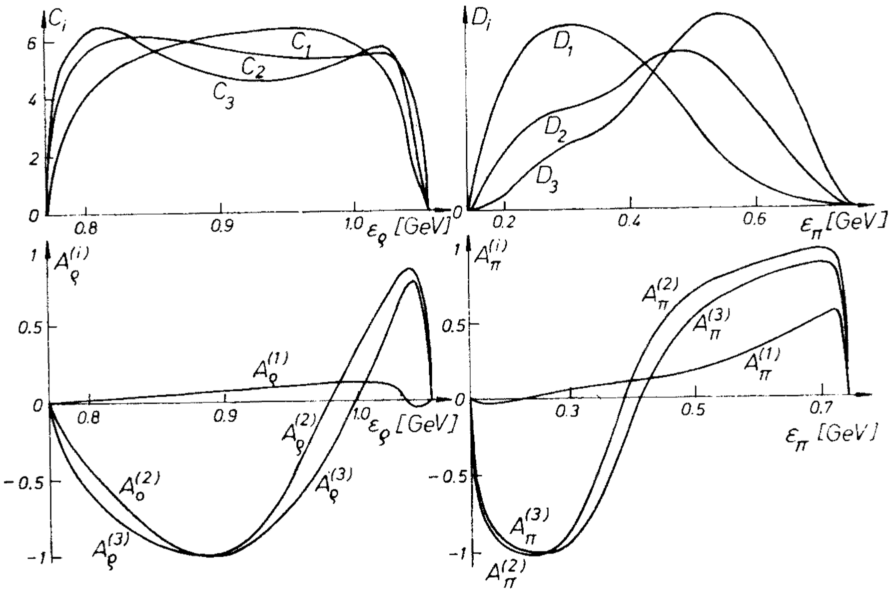

Fig. 3. The functions C_i, D_i, $A_\varrho^{(i)}$ and $A_\pi^{(i)}$

The functions D_i and $A_\pi^{(i)}$ are also plotted in Fig. 3. We take $g_A = 1$ and $m_\nu = 0$ for the numerical computations and ignore the second class current contribution.

In this approximation the total width is

$$w = 10^{-13}\left(g_1^2 m_A^2 1.5 + g_1 g_2 0.145 + \frac{g_2^2}{m_A^2} 0.0151\right), \tag{4.3}$$

we have used the values $m_A = 1.1$ GeV, $\Gamma_A = 0.3$ GeV [8].

There are experimental data [9] showing that the g_2/g_1 ratio cannot be large. Then we conclude (Eq. (4.3)) that the g_2 contribution is suppressed. This result is in good agreement with other investigations [10]. However, the asymmetries A_ρ and A_π strongly depend on the g_2 coupling (Fig. 3). One can use this fact to determine the g_2 coupling.

Now we have only $m_{\rho\pi}$ distribution in the $\tau \to \nu\varrho\pi$ decay [7]. This distribution may be obtained from Eq. (3.1) if we use the expression $m_{\rho\pi} = (2\varepsilon - 1)^{1/2}$. We see that the curve *1* (Fig. 4) corresponding to g_1^2 provides the best fit to the experimental data because the maxima of the experimental curve and curve *1* coincide within the experimental error. The curve *2* maximum (the term proportional to $g_1 g_2$) and curve *3* maximum (the term proportional to g_2^2) lie to the right.

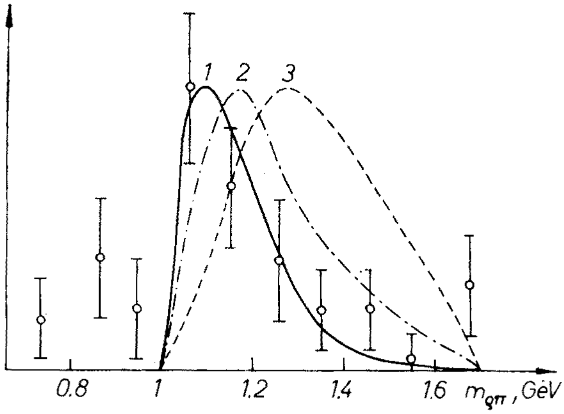

Fig. 4. The $dw/dm_{\varrho\pi}$ distribution (arbitrary units)

It is seen that the best fit to the experiment may be obtained if we neglect the g_2 coupling. Thus, we get from Eq. (4.3)

$$g_1^2 \cong 1.4,$$

(we used $B(\tau \to \nu\varrho\pi) = 10.4\%$ [4]).

In the same approximation this value of coupling corresponds to

$$\Gamma(A_1 \to \varrho\pi) \cong 26 \text{ MeV}.$$

We see that the recent experimental $\tau \to \nu\varrho\pi$ data lead to the strikingly narrow A_1 width, which is about 10% of the experimental value[1].

5. The ϱ^0 meson density matrix

The investigation of vector meson decay products permits one to get important information about the $\tau \to \nu\varrho\pi$ decay.

It is known that the angular distribution of the decay products is determined by the density matrix elements of the ϱ^0-meson ($\varrho^0 \to \pi^+(q)+\pi^-(q')$) [12]:

$$W(\theta, \varphi) = \frac{3}{4\pi}\Big[\varrho_{00}\cos^2\theta + \tfrac{1}{2}\sin^2\theta(\varrho_{11}+\varrho_{-1-1}) - \sin 2\theta\cos\varphi\,\frac{1}{\sqrt{2}}\,\mathrm{Re}\,(\varrho_{10}-\varrho_{-10})$$
$$-\mathrm{Re}\,\varrho_{1-1}\sin^2\theta\cos 2\varphi + \sin 2\theta\sin\varphi\,\frac{1}{\sqrt{2}}\,\mathrm{Im}\,(\varrho_{10}+\varrho_{-10}^{*}) + \sin^2\theta\sin 2\varphi\,\mathrm{Im}\,\varrho_{1-1}\Big],$$

[1] After completing this paper we learned about paper [11], which contained the same results. Using the current algebraic methods, the authors of [11] also obtained an acceptable $B(\tau \to \nu\varrho\pi)$ with the A_1 width being small.

where λ, λ' are the helicities of the vector meson. The space parity is violated in the $\tau \to \nu\varrho\pi$ decay that is why the density matrix elements satisfy only one condition: $\varrho_{\lambda\lambda'} = \varrho_{\lambda'\lambda}^{*}$. The normalized expression ($\sum_{\lambda} \varrho_{\lambda\lambda} = |M(\tau \to \nu\varrho\pi)|^2$) is given in the Appendix (we set $m_\nu = 0$).

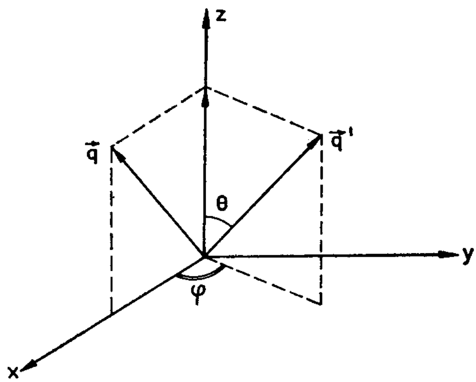

Fig. 5. The ρ^0-meson rest frame

It is seen that P-odd effects are characterized by $\sin\varphi$ and $\sin 2\varphi$ terms (Fig. 5) (φ is the azimuthal angle).

The authors would like to thank Drs. G. I. Gakh, Y. V. Kulish and A. P. Rekalo for many helpful discussions.

APPENDIX

A. The Dalitz plot

$$\frac{dw}{d\varepsilon_\pi d\varepsilon_\varrho} = \frac{G^2(1+\lambda^2)}{64\pi^2 m_\varrho^2}\Big\{[1+2(m_\varrho^2+m_\pi^2)+(m_\varrho^2-m_\pi^2)^2-4(1+m_\varrho^2+m_\pi^2)(\varepsilon_\pi+\varepsilon_\varrho)$$

$$+4(\varepsilon_\pi+\varepsilon_\varrho)^2]\,[|f_1|^2(m_\varrho^2(\varepsilon_\pi-1)+(1+m_\pi^2-2\varepsilon_\pi)\varepsilon_\varrho)$$

$$+|f_2|^2(m_\pi^2(\varepsilon_\varrho-1)+(1+m_\varrho^2-2\varepsilon_\varrho)\varepsilon_\pi)+\mathrm{Re}\,(f_1 f_2^*)$$

$$\times(1+m_\varrho^2+m_\pi^2-2\varepsilon_\pi(1+m_\varrho^2)-2\varepsilon_\varrho(1+m_\pi^2)+4\varepsilon_\pi\varepsilon_\varrho)]$$

$$+4|f_3|^2[m_\varrho^2(1-\varepsilon_\pi)+(1+m_\pi^2-2m_\varrho^2-2\varepsilon_\pi)\varepsilon_\varrho]$$

$$-4m_\varrho^2\,\mathrm{Re}\,(f_1 f_3^*)\Big[\varepsilon_\varrho(1-m_\pi^2)+\varepsilon_\pi(1+m_\pi^2-m_\varrho^2-2\varepsilon_\pi)$$

$$+\frac{\varepsilon_\varrho}{m_\varrho^2}(1+m_\pi^2-2\varepsilon_\pi)(1+m_\pi^2-2\varepsilon_\pi-2\varepsilon_\varrho)\Big]-4m_\varrho^2\,\mathrm{Re}\,(f_2 f_3^*)\Big[1+\tfrac{1}{2}m_\varrho^2$$

$$-m_\pi^2-\varepsilon_\pi(1+m_\pi^2-m_\varrho^2-2\varepsilon_\pi)+\varepsilon_\varrho(m_\pi^2-2)+\frac{1}{2m_\varrho^2}(1+m_\pi^2-2\varepsilon_\pi-2\varepsilon_\varrho)$$

$$\times(1+m_\pi^2-2\varepsilon_\pi-2\varepsilon_\varrho(1+m_\pi^2)+4\varepsilon_\pi\varepsilon_\varrho)\Big]$$

$$+\frac{\lambda}{(1+\lambda^2)}\operatorname{Re}(f_3^*f_4)(2\varepsilon_\varrho+2\varepsilon_\pi-1)(2\varepsilon_\pi-2\varepsilon_\varrho+m_\varrho^2-m_\pi^2)\Big\}.$$

B. The ϱ-meson density matrix

$$\varrho_{mn}=\varrho_{nm}^*,\quad m_\tau=1,\quad m_\nu=0.$$

$$\varrho_{+0}\equiv\varrho_{+0}^{s}+\varrho_{+0}^{a},\quad \varrho_{0-}\equiv\varrho_{0-}^{s}+\varrho_{0-}^{a},\quad \varrho_{\pm\pm}\equiv\varrho_{\pm\pm}^{s}+\varrho_{\pm\pm}^{a},$$

$$\varrho_{0-}^{s}=\varrho_{+0}^{s},\quad \varrho_{0-}^{a}=-\varrho_{+0}^{a},\quad \varrho_{--}^{s}=\varrho_{++}^{s},\quad \varrho_{--}^{a}=-\varrho_{++}^{a}.$$

$$a\equiv 1-m_\varrho p_{1t},\quad b=p_{1t}-m_\varrho,\quad c=p_{1t}p_{2z}+p_{2t}p_{1z},\quad d\equiv q_zp_{2t}-q_tp_{2z},$$

$$g\equiv S\cdot p_2q_z-q\cdot p_{2z}S_z-q\cdot Sp_{2z},\quad h=\frac{1}{q_x}(S_x+iS_y).$$

$$R=|f_1|^2[(1+\lambda^2)(2k\cdot p_1k\cdot p_2-p_1\cdot p_2m_\varrho^2)+2\lambda(S\cdot p_2m_\varrho^2-2S\cdot kk\cdot p_2)]$$

$$+|f_2|^2[(1+\lambda^2)(2q\cdot p_1q\cdot p_2-m_\pi^2p_1\cdot p_2)+2\lambda(S\cdot p_2m_\pi^2-2q\cdot p_2S\cdot q)]$$

$$+4\operatorname{Re}(f_1f_2^*)[(1+\lambda^2)(q\cdot p_1k\cdot p_2+q\cdot p_2k\cdot p_1-q\cdot kp_1\cdot p_2)+2\lambda(S\cdot p_2k\cdot q$$

$$-q\cdot p_2S\cdot k-S\cdot qk\cdot p_2)];$$

$$\tfrac{1}{2}\varrho_{00}=q_z^2R+2\operatorname{Re}(f_2f_3^*)q_z[(1+\lambda^2)(p_{2z}-m_\varrho^2c)+2\lambda g]$$

$$+2\operatorname{Re}(f_1f_3^*)m_\varrho q_z[(1+\lambda^2)c-2\lambda(p_{2t}S_z+S_tp_{2z})]$$

$$+|f_3|^2[(1+\lambda^2)(p_{1z}p_{2z}+p_{1t}p_{2t})-2\lambda(S\cdot p_2+2S_zp_{2z})]$$

$$+2(1+\lambda^2)m_\varrho S_yq_xq_z\operatorname{Im}\left(f_1f_2^*p_{1z}q_z-f_1f_3^*-f_2f_3\frac{b}{m_\varrho}\right);$$

$$\varrho_{++}^{s}=q_x^2R+2|f_3|^2[(1+\lambda^2)p_1\cdot p_2+2\lambda(p_{2z}S_z-p_{2t}S_t)]$$

$$+2m_\varrho\operatorname{Re}(f_1f_3^*)q_x[2\lambda(q_xS_t-p_{2t}S_x)-(1+\lambda^2)q_xp_{1t}]$$

$$-2\operatorname{Re}(f_2f_3^*)q_x[(1+\lambda^2)q_xa+2\lambda(q\cdot p_2S_x+q_xS_tm_\varrho)]$$

$$+2(1+\lambda^2)q_xS_y(df_2f_3^*+f_1f_2^*m_\varrho q_x^2p_{1z}-m_\varrho p_{2z}f_1f_3^*);$$

$$\varrho_{++}^{a}=|f_3|^2[(1+\lambda^2)(p_{2t}S_z-p_{2z}S_t)+2\lambda(p_{1t}p_{2z}-p_{1z}p_{2t})]$$

$$+2\,\mathrm{Re}\,(f_1 f_3^*) m_\varrho q_x [2\lambda q_x p_{1z} - (1+\lambda^2)(q_x S_z + p_{2z} S_x)]$$

$$+2q_x\,\mathrm{Re}\,(f_3 f_3^*)\,[(1+\lambda^2)(S_x d - q_x S_z b + q_x p_{1z} S_t) - 2\lambda m_\varrho q_x p_{1z}]$$

$$-4\lambda q_x S_y\,\mathrm{Im}\,(f_1 f_3^* m_\varrho p_{2t} + f_2 f_3^* q\cdot p_2);$$

$$\frac{1}{q_x^2}\varrho_{+-} = R + 4\lambda |f_3|^2 h + 2(1+\lambda^2)\,\mathrm{Im}\,(f_1 f_2^*) m_\varrho q_x S_y p_{1z}$$

$$+2i\,\mathrm{Im}\,(f_1 f_3^*) m_\varrho [(1+\lambda^2)(p_{2z} h + S_z) - 2\lambda p_{1z}] - 2i\,\mathrm{Im}\,(f_2 f_3^*)$$

$$\times [(1+\lambda^2)(dh + p_{1z} S_t - S_z b) - 2\lambda m_\varrho p_{1z}] + 2\,\mathrm{Re}\,(f_1 f_3^*) m_\varrho$$

$$\times \left[2\lambda\left(S_t - \frac{S_x}{q_x} p_{2t}\right) - (1+\lambda^2) p_{1t}\right] - 2\,\mathrm{Re}\,(f_2 f_3^*)\left[(1+\lambda^2) a\right.$$

$$\left. + 2\lambda\left(\frac{S_x}{q_x} q\cdot p_2 + m_\varrho S_t\right)\right];$$

$$\frac{1}{\sqrt{2}\,q_x}\varrho_{t0}^{\mathrm{s}} = q_z R + |f_3|^2 [2\lambda(S_z - p_{2z} h) - (1+\lambda^2) p_{1z}] + m_\varrho\,\mathrm{Re}\,(f_1 f_3^*)$$

$$\times \{(1+\lambda^2)(c - q_z p_{1t}) - 2\lambda[p_{2t}(S_z + q_z h) + S_t(p_{2z} - q_z)]\}$$

$$+\mathrm{Re}\,(f_2 f_3^*)\,\{(p_{2z} - q_z a - m_\varrho c)(1+\lambda^2) + 2\lambda[g - q_z(m_\varrho S_t + q\cdot p_2 h)]\}$$

$$+2(1+\lambda^2)\,\mathrm{Im}\,(f_1 f_2^*) m_\varrho q_x S_y q_z p_{1z} + i\,\mathrm{Im}\,(f_1 f_3^*) m_\varrho q_z \left[(1+\lambda^2)\right.$$

$$\left.\times \left(S_z + h p_{2z} + \frac{i}{q_z} S_y q_x\right) - 2\lambda p_z\right] - i\,\mathrm{Im}\,(f_2 f_3^*) q_z \left[(1+\lambda^2)\right.$$

$$\left.\times \left(hd + p_{1t} S_t - b S_z - \frac{ib}{q_z} q_x S_y\right) - 2\lambda m_\varrho p_{1z}\right];$$

$$\frac{1}{\sqrt{2}\,q_x}\varrho_{t0}^{\mathrm{a}} = |f_3|^2 [2\lambda p_{1z} - (1+\lambda^2)(S_t + h p_{2t})] + \mathrm{Re}\,(f_1 f_3^*) m_\varrho q_z$$

$$\times \left[2\lambda p_{1z} - (1+\lambda^2)\left(p_{2z} h + S_z - \frac{iS_y}{q_z} q_x\right)\right] + \mathrm{Re}\,(f_3 f_3^*) q_z$$

$$\times \left[(1+\lambda^2)\left(dh + p_{1z} S_t - b S_z + i b q_x S_y \frac{1}{q_z}\right) - 2\lambda m_\varrho p_{1z}\right]$$

$$+\mathrm{Im}\,(f_1 f_3^*) m_\varrho [(1+\lambda^2) p_{1z}(p_{1t} + p_{2t}) + 2\lambda(p_{2t}(q_z h - S_z) - S_t p_{1z})]$$

$$+i\,\mathrm{Im}\,(f_2 f_3^*)\,[(1+\lambda^2) p_{1z} q\cdot(p_1 + p_2) + 2\lambda(q\cdot p_2(q_z h - S_z) - S\cdot q p_{1z})].$$

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