LIGHT MESON DECAY IN THE $C^3P_0$ MODEL

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Having its origin in a successful mapping technique, the Fock-Tani formalism, the corrected $^3P_0$ model ($C^3P_0$) retains the basic aspects of the $^3P_0$ predictions with the inclusion of bound-state corrections. Evaluation of the decay amplitudes has been performed for open-flavor strong decays in the light meson sector. The bound-state corrections introduce a fine-tuning for the former $^3P_0$ model, in particular, the adjustment of the $D/S$ ratios in $b_1 \to \omega \pi$, $a_1 \to \rho \pi$ and $h_1 \to \rho \pi$ decays.

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I. INTRODUCTION

A mapping technique long used in atomic physics [1]-[3], the Fock-Tani formalism (FTf), has been adapted, in previous publications [4]-[9], in order to describe hadron-hadron scattering interactions with constituent interchange. Recently this technique has been extended to meson decay [10]. The novel feature of this approach is the presence of bound-state corrections (BSC) in the decay amplitude. A necessary ingredient in the formalism is the definition of the microscopic interaction Hamiltonian between the elementary constituents.

Open-flavor strong decays are successfully described in the context of the the $^3P_0$ model, which considers only OZI-allowed strong-interaction decays and was introduced over thirty years ago by Micu [11]-[16]. In the FTf, if one starts from a microscopic $q\bar{q}$ pair-creation interaction, in lowest order, the $^3P_0$ results are reproduced. In higher orders of the formalism corrections due to the bound-state nature of the mesons are present and the $q\bar{q}$ interaction strength is modified. This new model is called the Corrected $^3P_0$ model ($C^3P_0$) [10]. Light meson decay and other meson sectors have been studied by T. Barnes et al. [17]-[20] with the $^3P_0$ model. In their formulation two basic parameters are adjusted to data, $\gamma$ (the interaction strength) and $\beta$ (the wave function’s extension parameter). They found optimum values for these parameters near $\gamma = 0.5$ and $\beta = 0.4$ GeV.

In the present work, we employ the FTf to the light 1S and 1P decays and a comparison is made with the usual $^3P_0$ results. In the next section we briefly review the basic aspects of the formalism and the $C^3P_0$ derivation. Section III is dedicated to obtain the decay rates of seven light mesons, followed by the summary and conclusions.

II. THE $C^3P_0$ MODEL

In this section we present a brief review of the formal aspects regarding the Fock-Tani mapping procedure and how it is implemented to quark-antiquark meson states [4, 5]. The starting point of the Fock-Tani formalism is the definition of single composite bound states. We write a single-meson state in terms of a meson creation operator $M_\alpha^\dagger$ as

$$|\alpha\rangle = M_\alpha^\dagger |0\rangle,$$

(1)

where $|0\rangle$ is the vacuum state. The meson creation operator $M_\alpha^\dagger$ is written in terms of constituent quark and antiquark creation operators $q^\dagger$ and $\bar{q}^\dagger$,

$$M_\alpha^\dagger = \Phi_{\mu \nu}^\alpha q_\mu^\dagger \bar{q}_\nu^\dagger,$$

(2)

$\Phi_{\mu \nu}^\alpha$ is the meson wave function and $q_\mu^\dagger |0\rangle = \bar{q}_\nu^\dagger |0\rangle = 0$. The index $\alpha$ identifies the meson quantum numbers of space, spin and isospin. The indices $\mu$ and $\nu$ denote the spatial, spin, flavor, and color quantum numbers of the constituent quarks. A sum over repeated indices is implied. The meson operators satisfy the following non-canonical commutation relations

$$[M_\alpha, M_\beta^\dagger] = \delta_{\alpha \beta} - M_{\alpha \beta}^*, \quad [M_\alpha^\dagger, M_\beta] = 0,$$

(3)

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where
\[ M_{\alpha\beta} = \Phi^{*\mu\nu} \Phi^{*\sigma\tau} \delta_{\alpha\mu} \delta_{\beta\nu} + \Phi^{*\mu\nu} \Phi^{*\sigma\tau} \delta_{\alpha\nu} \delta_{\beta\mu}. \]  

A transformation is defined such that a single-meson state \(|\alpha\rangle\) is redescribed by an ("ideal") elementary-meson state by
\[ |\alpha\rangle \rightarrow U^{-1} |\alpha\rangle = m_{\alpha}^{|0\rangle}, \]
where \(m_{\alpha}^{|0\rangle}\) an ideal meson creation operator. The ideal meson operators \(m_{\alpha}^{|0\rangle}\) and \(m_{\alpha}\) satisfy, by definition, canonical commutation relations
\[ [m_{\alpha}, m_{\beta}^{|0\rangle}] = \delta_{\alpha\beta}, \quad [m_{\alpha}, m_{\beta}] = 0. \]

Once a microscopic interaction Hamiltonian \(H_I\) is defined, at the quark level, a new transformed Hamiltonian can be obtained. This effective interaction, the Fock-Tani Hamiltonian \((H_{FT})\), is obtained by the application of the unitary operator \(U\) on the microscopic Hamiltonian \(H_I\), i.e., \(H_{FT} = U^{-1}H_IU\). The transformed Hamiltonian describes all possible processes involving mesons and quarks. In \(H_{FT}\) there are higher order terms that provide bound-state corrections to the lower order ones. The basic quantity for these corrections is the bound-state kernel \(\Delta\) defined as
\[ \Delta(\rho\tau; \mu\nu) = \Phi^{*\rho\tau} \Phi^{*\mu\nu}. \]

The physical meaning of the \(\Delta\) kernel becomes evident, in the sense that it modifies the quark-antiquark interaction strength \([4, 5, 10]\).

In the present calculation, the microscopic interaction Hamiltonian is a pair creation Hamiltonian \(H_{q\bar{q}}\) defined as
\[ H_{q\bar{q}} = V_{\mu\nu} q_{\mu}^{\dagger} q_{\nu}^{\dagger}, \]
where \(V_{\mu\nu}\) is given by
\[ V_{\mu\nu} \equiv 2 m_q \gamma^\mu (\bar{p}_\mu + \bar{p}_\nu) \bar{u}_{s_f, f_c} (\bar{p}_\mu) \nu_{s_f, f_c} (\bar{p}_\nu), \]
where \(\gamma\) is the pair production strength. The pair production is obtained from the non-relativistic limit of \(H_{q\bar{q}}\) involving Dirac quark fields \([17]\). Applying the Fock-Tani transformation to \(H_{q\bar{q}}\) one obtains the effective Hamiltonian that describes a decay process. In the FTf perspective a new aspect is introduced to meson decay: bound-state corrections. The lowest order correction is one that involves only one bound-state kernel \(\Delta\). The bound-state corrected, \(C^3P_0\) Hamiltonian, is
\[ H^{C^3P_0} = -\Phi^{*\alpha\beta} \Phi^{*\lambda\tau} \Phi^{*\omega\sigma} V^{C^3P_0} m_{\alpha}^{|1\rangle} m_{\beta}^{|0\rangle} m_\gamma, \]
where \(V^{C^3P_0}\) is a condensed notation for
\[ V^{C^3P_0} = \left[ \delta_{\mu\lambda} \delta_{\nu\xi} \delta_{\delta\rho} \delta_{\sigma\tau} - \frac{1}{2} \delta_{\sigma\xi} \delta_{\lambda\omega} \Delta(\rho\tau; \mu\nu) + \frac{1}{4} \delta_{\sigma\xi} \delta_{\lambda\mu} \Delta(\rho\tau; \omega\nu) \right] V_{\mu\nu}. \]

In the ideal meson space the initial and final states involve only ideal meson operators \(|A\rangle = m_{\alpha}^{|0\rangle}\) and \(|BC\rangle = m_{\beta}^{|0\rangle}\). The \(C^3P_0\) amplitude is obtained by the following matrix element,
\[ \langle BC|H^{C^3P_0}|A\rangle = \delta(\bar{P}_A - \bar{P}_B - \bar{P}_C) h^{C^3P_0}_{ji} \]
The \(h^{C^3P_0}_{ji}\) decay amplitude is combined with relativistic phase space, resulting in the differential decay rate
\[ \frac{d\Gamma_{A\rightarrow BC}}{d\Omega} = 2\pi P \frac{E_B E_C}{M_A} |h^{C^3P_0}_{ji}|^2 \]
which, after integration in the solid angle \(\Omega\), a usual choice for the meson momenta is made: \(\bar{P}_A = 0\) (\(P = |\bar{P}_B| = |\bar{P}_C|\).
III. LIGHT MESON DECAY IN THE $C^3P_0$ MODEL

We shall apply the model described in the former section to the light meson sector, in particular 1S and 1P decay processes: $\rho \rightarrow \pi \pi$, $b_1 \rightarrow \omega \pi$, $a_1 \rightarrow \rho \pi$, $a_2 \rightarrow \rho \pi$, $h_1 \rightarrow \rho \pi$, $f_0 \rightarrow \pi \pi$ and $f_2 \rightarrow \pi \pi$. The major issue in this calculation is the value of the decay amplitude $h_{fi}^{C^3P_0}$. To evaluate this quantity we must define the general non-relativistic meson wave function $\Phi_\alpha$, which can be written as a direct product

$$\Phi_\alpha = \chi^{s_1 s_2} \sum f_{f_1 f_2} C_{c_1 c_2} \Phi_{nl}(\vec{p}_\alpha - \vec{p}_1 - \vec{p}_2),$$

(14)

where the components are: spin $\chi^{s_1 s_2}$, flavor $f_{f_1 f_2}$, color $C_{c_1 c_2}$ and space $\Phi_{nl}(\vec{p}_\alpha - \vec{p}_1 - \vec{p}_2)$. In all our calculations the color component will be given by

$$C_{c_1 c_2} = \frac{1}{\sqrt{3}} \delta^{c_1 c_2}. $$

(15)

We assume that the spatial part is defined as harmonic oscillator wave functions

$$\Phi_{nl}(\vec{p}_\alpha - \vec{p}_1 - \vec{p}_2) = \delta(\vec{p}_\alpha - \vec{p}_1 - \vec{p}_2) \phi_{nl}(\vec{p}_1, \vec{p}_2),$$

(16)

where $\phi_{nl}(\vec{p}_1, \vec{p}_2)$ is given by

$$\phi_{nl}(\vec{p}_1, \vec{p}_2) = \left( \frac{1}{2\beta} \right)^{l+\frac{1}{2}} N_{nl} |\vec{p}_1 - \vec{p}_2|^l \exp \left( -\frac{(\vec{p}_1 - \vec{p}_2)^2}{8\beta^2} \right) L_n^{l+\frac{1}{2}} \left( \frac{(\vec{p}_1 - \vec{p}_2)^2}{4\beta^2} \right) Y_{lm}(\Omega_{\vec{p}_1 - \vec{p}_2}),$$

(17)

with $p_{i,j}$ the internal momentum, the spherical harmonic $Y_{lm}$ and $\beta$ a scale parameter. The normalization constant $N_{nl}$ dependent on the radial and orbital quantum numbers

$$N_{nl} = \left[ \frac{2(n!)}{\beta^3 \Gamma(n + l + 3/2)} \right]^{\frac{1}{2}} .$$

(18)

The Laguerre polynomials $L_{n}^{l+\frac{1}{2}}(p)$ are defined as

$$L_{n}^{l+\frac{1}{2}}(p) = \sum_{k=0}^{n} \frac{(-)^k \Gamma(n + l + 3/2)}{k! (n-k)! \Gamma(k + l + 3/2)} p^k.$$

(19)

The bound-state kernel’s definition in (17) implies in an additional element, due to the contraction in the $\alpha$ index, a sum over species requirement $[1, 3, 10]$. A question that naturally arises is: which states to include in this sum? We shall adopt in our calculation a restrictive choice: include in the sum only the particles that are present in the final state. For the example, in the $\rho^+ \rightarrow \pi^0 + \pi^+$, decay, $\Delta(\rho \pi; \lambda \nu)$ will have two contributions set to the quantum numbers of $\pi^0$ and $\pi^+$. In the $b_1^+ \rightarrow \omega + \pi^+$ decay, two contributions come from $\omega$ and $\pi^+$. Similarly, the $a_1^+ \rightarrow \rho^+ + \pi^0$ decay shall be corrected by the final state mesons $\rho^+$ and $\pi^0$. The other decays follow the same logic.

After calculating the matrix element in Eq. (12), the general decay amplitude can be written as

$$h_{fi}^{C^3P_0} = \frac{\gamma}{\pi^{1/4} \beta^{1/2}} M_{fi},$$

(20)

where

$$M_{fi}^{\rho^+ \rightarrow \pi^0} = C_{f_1}^{0, 0} Y_{11} (\Omega_x),$$

$$M_{fi}^{f_2 \rightarrow \pi^+} = C_{f_1}^{2, 0} Y_{22} (\Omega_x),$$

$$M_{fi}^{f_0 \rightarrow \pi^-} = C_{f_1}^{0, 0} Y_{00} (\Omega_x),$$

$$M_{fi}^{a_1 \rightarrow \rho^+} = C_{f_1}^{2, 1} Y_{21} (\Omega_x),$$

$$M_{fi}^{b_1 \rightarrow \omega \pi^+} = C_{f_1}^{1, 0} Y_{00} (\Omega_x) + C_{f_1}^{1, 1} Y_{20} (\Omega_x),$$

$$M_{fi}^{a_1 \rightarrow \rho^+} = C_{f_1}^{0, 0} Y_{00} (\Omega_x) + C_{f_1}^{2, 2} Y_{20} (\Omega_x),$$

$$M_{fi}^{h_1 \rightarrow \rho^+} = C_{f_1}^{0, 0} Y_{00} (\Omega_x) + C_{f_1}^{2, 1} Y_{20} (\Omega_x),$$

(21)
\( C_{LS} \) coefficients are

\[
\begin{align*}
C_{i0}^\rho & \equiv -x \left[ \frac{2^{9/2}}{3^3} e_1(x) + \frac{2^{11/2}}{3^{3/2}7^{5/2}} e_2(x) \right] \\
C_{20}^\rho & \equiv x^2 \left[ \frac{2^{11/2}}{3^{15/2}} e_1(x) - \frac{2^{17/2}}{3^{25/2}7^{7/2}} e_2(x) \right] \\
C_{i0}^g & \equiv \frac{2^4}{3^3} \left[ 1 - \frac{2}{9} x^2 \right] e_1(x) - \frac{2^5}{7^{5/3}} \left[ 1 - \frac{8}{21} x^2 \right] e_2(x) \\
C_{21}^g & \equiv -x^2 \left[ \frac{2^{15/2}}{3^{7/2}7^{5/2}} e_1(x) - \frac{2^7}{3^{7/2}7^{11/2}} e_2(x) \right] \\
C_{i0}^h & \equiv -\frac{2^4}{3^5/2} \left[ 1 - \frac{2}{9} x^2 \right] e_1(x) + \frac{2^5}{7^{5/2}} \left[ 1 - \frac{8}{21} x^2 \right] e_2(x) \\
C_{21}^h & \equiv -x^2 \left[ \frac{2^{11/2}}{3^{7/2}7^{11/2}} e_1(x) - \frac{2^{17/2}}{3^{7/2}7^{13/2}} e_2(x) \right] \\
C_{i0}^a & \equiv \frac{2^{9/2}}{3^{3/2}} e_1(x) - \frac{2^{11/2}}{7^{5/3}} e_2(x) \\
C_{21}^a & \equiv -x^2 \left[ \frac{2^{5/2}}{3^{9/2}} e_1(x) - \frac{2^{7/2}}{3^{9/2}7^{11/2}} e_2(x) \right] \\
C_{i0}^b & \equiv \frac{2^4}{3^{9/2}} \left[ 1 - \frac{2}{9} x^2 \right] e_1(x) + \frac{2^5}{7^{5/2}} \left[ 1 - \frac{8}{21} x^2 \right] e_2(x) \\
C_{21}^b & \equiv -x^2 \left[ \frac{2^{11/2}}{3^{9/2}7^{11/2}} e_1(x) - \frac{2^{17/2}}{3^{9/2}7^{13/2}} e_2(x) \right]
\end{align*}
\]

with \( x = P/\beta; e_1(x) = \exp \left( -x^2/12 \right) \) and \( e_2(x) = \exp \left( -9x^2/28 \right) \). The decay rates are given by the following general expression

\[
\Gamma = 2\pi^{1/2} \gamma^2 E_B E_C \frac{M_A}{x} \sum_{LS} C_{LS}^2.
\]

The D/S ratio for the \( a_1, b_1 \) and \( h_1 \) mesons is a very sensitive experimental quantity and function of the coefficients \( C_{LS} \) in (22). In particular

\[
\left. \frac{a_D}{a_S} \right|_{a_1 \to \rho \pi} = \frac{C_{a1}^{a1}}{C_{a1}^{01}} ; \quad \left. \frac{a_D}{a_S} \right|_{b_1 \to \omega \pi} = \frac{C_{b1}^{b1}}{C_{b1}^{01}} ; \quad \left. \frac{a_D}{a_S} \right|_{h_1 \to \rho \pi} = \frac{C_{h1}^{h1}}{C_{h1}^{01}}.
\]

Replacing (22) in (24), we find

\[
\left. \frac{a_D}{a_S} \right|_{a_1 \to \rho \pi} = -x^2 \left[ \frac{2^{1/2}}{3^3} e_1(x) - \frac{2^{5/2}3^{3/2}7^{5/2}}{7^{11/2}} e_2(x) \right] \\
\left. \frac{a_D}{a_S} \right|_{b_1 \to \omega \pi} = x^2 \left[ \frac{2^{3/2}}{3^3} e_1(x) - \frac{2^{7/2}}{3^{3/2}7^{7/2}} e_2(x) \right] \\
\left. \frac{a_D}{a_S} \right|_{h_1 \to \rho \pi} = x^2 \left[ \frac{2^{3/2}}{3^3} e_1(x) - \frac{2^{7/2}}{3^{3/2}7^{9/2}} e_2(x) \right].
\]

In the numerical calculation the meson masses are assumed the following: \( M_\pi = 0.139 \text{ GeV}, M_\rho = 0.775 \text{ GeV}, M_\omega = 0.782 \text{ GeV}, M_{h_1} = 1.170 \text{ GeV}, M_{a_1} = 1.230 \text{ GeV}, M_{b_1} = 1.229 \text{ GeV}, M_{f_2} = 1.275 \text{ GeV}, M_{f_0} = 1.370 \text{ GeV}, \)
TABLE I: Decay rates $^3P_0$ ($\gamma = 0.506; \beta = 0.397$ GeV) and $C^3P_0$ ($\gamma = 0.535; \beta = 0.387$ GeV)

| Decay | Exp [21] | $^3P_0$ | $C^3P_0$ | D/S |
|-------|----------|--------|----------|-----|
| $\rho \to \pi\pi$ | 149.4 | 81 | 111 | |
| $f_2 \to \pi\pi$ | 156.7 | 170 | 181 | |
| $a_2 \to \rho\pi$ | 75 (3π mode) | 52 | 47 | |
| $a_1 \to \rho\pi$ | 250 to 600 | 543 | 536 | |
| $b_1 \to \omega\pi$ | 142 | 143 | 143 | |
| $h_1 \to \rho\pi$ | 360 | 378 | 374 | |
| $f_0 \to \pi\pi$ | 126 to 460 | 225 | 198 | |

$M_{a_2} = 1.318$ GeV [21]. To adjust the model one has to minimize $R$, defined by

$$R^2 = \sum_{i=1}^{7} \left[ a_i(\gamma, \beta) - 1 \right]^2$$

with $a_i(\gamma, \beta) = \Gamma_i^{\text{hy}}(\gamma, \beta)/\Gamma_i^{\text{exp}}$. To compare the $^3P_0$ model with its corrected version, the minimum value for $R$ is obtained for $\gamma = 0.506$ and $\beta = 0.397$ GeV ($R = 0.559$). The inclusion of the correction term reduces the $R$ value to 0.486 with slightly different values for $\gamma = 0.535$ and $\beta = 0.387$ GeV. A clear demonstration that the bound-state correction globally improves the fit.

The values for $\gamma$ and $\beta$ are used for the seven mesons and presented in Table I with the D/S ratios. Some comments should be made about these results. The $b_1 \to \omega\pi$ channel is experimentally well known and in both models $\Gamma$ and D/S ratios are the same. The most important discrepancy in Table II is $\rho \to \pi\pi$, which is well known to be a problem relative to the decays of P-wave $q\bar{q}$ mesons in the $^3P_0$ model [17]. The corrected model has an important improvement in this channel. In this fit the only channel where $^3P_0$ model has better estimate compared to the corrected model is for $f_2$ decay. The $a_2$ decay, for example, is one of the three channels in a 3π mode. The total experimental decay rate for the 3π mode is 75 MeV, composed of three channels $a_2 \to \rho(770)\pi$, $a_2 \to f_2(1270)\pi$ and $a_2 \to (1450)\pi$. In our calculation, only the first channel was evaluated and it shows a smaller contribution to the total value of this mode in comparison to the original $^3P_0$ model. The ratio for $h_1 \to \rho\pi$, which has not been measured, is theoretically close to $b_1 \to \omega\pi$ to within small phase space differences, since these are both $^1P_1 \to ^1S_1 + ^1S_0$ decays. Similar to the $b_1$ decay, as expected, the $h_1$ channel in both models has close values for $\Gamma$ and D/S ratios. The $f_0(1370)$ decay to 2π has a wide range of values in PDG [21], consistent with both models. In our calculation $f_0(1370)$ is regarded only as a $n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$ state. In the literature, to the lowest order, this scalar meson has been considered as a mixture of the scalar two gluon glueball $G$ with quarkonia states $n\bar{n}$ and $s\bar{s}$ [22, 23].

IV. SUMMARY AND CONCLUSIONS

In this paper we have tested, for the first time, an alternative approach for meson decay, the $C^3P_0$ model derived from the mapping technique, known as the Fock-Tani formalism. The model preserves the essential predictions of the $^3P_0$ approach, introducing a novel feature of bound-state corrections to the decay amplitude. The results obtained seem promising, in particular an important improvement is seen in the decay rate of $\rho \to \pi\pi$ and in the D/S ratio of $a_1 \to \rho\pi$. From this study we should say that, although important as a fine-tuning to decay processes, the bound-state correction should represent a small contribution to dynamics due to the extended nature of the mesons. Future calculations can shed light to this aspect.

For strange mesons, glueball candidates or in the charmed sector the inclusion of different $\beta$ values may become necessary. The inclusion of the full meson octet, in the evaluation of the bound-state kernel $\Delta$, may provide an additional adjustment in fitting the model. The examples studied here are encouraging, but a more extensive survey in other meson sectors would be a necessary next step.

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