The decay rate of J/ψ to $\Lambda_c + \overline{\Sigma^+}$ in SM and beyond

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Abstract

With rapid growth of the database of the BES III and the proposed super flavor factory, measurement on the rare J/ψ decays may be feasible, especially the weak decays into baryon final states. In this work we study the decay rate of J/ψ to $\Lambda_c + \overline{\Sigma^+}$ in the SM and physics beyond the SM (here we use the unparticle model as an example). The QPC model is employed to describe the creation of a pair of $q\bar{q}$ from vacuum. We find that the rate of $J/\psi \to \Lambda_c + \overline{\Sigma^+}$ is at order of 10^{-10} in the SM, whereas the contribution of the unparticle is too small to be substantial. Therefore if a large branching ratio is observed, it must be due to new physics beyond SM, but by no means the unparticle.

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I. INTRODUCTION

It is well known that J/ψ decays overwhelmingly via strong and electromagnetic interactions, which are the OZI [1] suppressed processes. The goal of the research on J/ψ is not only to study the low energy QCD effects which determine the hadronic transition matrix elements, but also to find evidence of new physics in the concerned processes. Since the strong interaction QCD dominates, the contributions of new physics whose effects are in general much smaller, would be drowned by the QCD background and unobservable. To observe the processes where new physics may play more important role, we need to turn to the rare decays of J/ψ. One obvious field is the weak decays of J/ψ. Of course, due to the dominance of the strong interaction at J/ψ decays, the branching ratios of such weak decays are very small, so that measurements on them are extremely difficult.

In our earlier papers [2] the branching ratios of semi-leptonic and hadronic weak decays of J/ψ into two mesons (vector or pseudoscalar) are evaluated in the framework of the standard model (SM) and we found that they are of order of 10^{-9} to 10^{-11} which is much beyond the range of detection for any present machines. However, the situation is not so pessimistic, as the database accumulated at the BES III is becoming large and the proposed super-flavor factory will be running in the future, measurements on the weak decays may be possible. It is expected that if some sizable signals for the weak decays are observed (even still very small), one would conclude that there is new physics or new mechanism beyond our present knowledge. Moreover, as stated above, the main goal is to see if for some modes the ratios obviously exceed the values theoretically calculated in terms of SM, if yes, it would be clear signals for new physics beyond SM. That is what we expect.

For a long time more researches focus on mesons than baryons. The reason is that there are three constituents in baryon and there are only two in mesons in comparison. The three-body system indeed is much more complicated than the two-body one, even in the classical physics. Another reason is that the data concerning baryon final states are not as abundant as for mesons, so that it is harder to fix the model parameters. But now a larger database on baryon final states will be available at the LHCb and other experiments such as BES-III, especially the proposed super-flavor factory. Since baryons possess different characteristic from mesons a thorough study on the production and decay processes of baryon is becoming an important field which will provide a clearer insight into the structure of hadron, underlying physics, mechanics and the fundamental interactions, especially such processes may be more sensitive to new physics beyond the SM. On the other hand we will also have a chance to test some models and constrain their parameter space. Moreover, the plan of studying baryon case at BES III is substantialized , so that we would like to pay more attention to the weak decays of J/ψ into baryon final state, even though corresponding processes are rare.

In this paper we study the production of $J/\psi \to \Lambda_c + \overline{\Sigma^+}$ which occurs via weak interaction. Concretely, we will calculate the rate in the frameworks of the SM and beyond. As an example for the model beyond the SM, we employ the unparticle scenario proposed by Georgi [3]. Some phenomenology concerning the unparticle scenario has been explored [4, 5] and constraints on its parameter space were set by fitting observational data. Therefore, the concerned model parameters have been determined and there is not much room for adjusting them. In this work we will estimate the contributions from both the SM particles and the unparticle as the intermediate agent to $J/\psi \to \Lambda_c + \overline{\Sigma^+}$. A comparison between their contributions may shed some light on the role of the possible models beyond the SM.

Since three pairs of quarks and antiquarks are produced from either the intermediate bosons or vacuum, the processes are more complex than the case for mesons. But it does not cause any principal difficulty. In this work we will employ the Quark-Pair-Creation model(QPC model)[6–8] to deal with the quark pair production and the harmonic oscillator wave function for the hadrons. The quark-antiquark pair is created from vacuum in this model and the essence of the picture is that the quark-pair is created from the soft gluons radiated from the quark-antiquark legs.

The key point is to evaluate the transition matrix elements between hadrons which are governed by the non-perturbative QCD. The harmonic oscillator wave function is used to describe the bound states in this model and the corresponding non-perturbative effect is included in the model-parameter R .

This paper is organized as follows: after the introduction, in section II and III we formulate the transition amplitude of the process $J/\psi \to \Lambda_c + \overline{\Sigma^+}$ in SM and unparticle model respectively. The last section is devoted to our conclusion and discussions.

II. $J/\psi \to \Lambda_c + \overline{\Sigma^+}$ IN SM

In this section we are going to calculate the decay widths of $J/\psi \to \Lambda_c + \overline{\Sigma^+}$ in SM.

A. Feynman diagram

We show the Feynman diagrams in Fig.1 and the left one is that in the SM. The c quark directly transits into the finial Λ_c as a spectator and $\bar{c}$ decays into $\bar{s}$ and $d\bar{u}$ via a W-boson exchange. A pair of $u\bar{u}$ is created from the vacuum. Then those quarks and anti-quarks eventually hadronize into Λ_c and $\overline{\Sigma^+}$.

B. the QPC model

In the Fig.1 a pair of $u\bar{u}$ is created from vacuum. The QPC model is also named as 3P0 model since the quantum number of the vacuum is $J^{PC} = 0^{++}$. In the QPC model the pair of quark-antiquark is created from the vacuum while other quarks are unaffected.

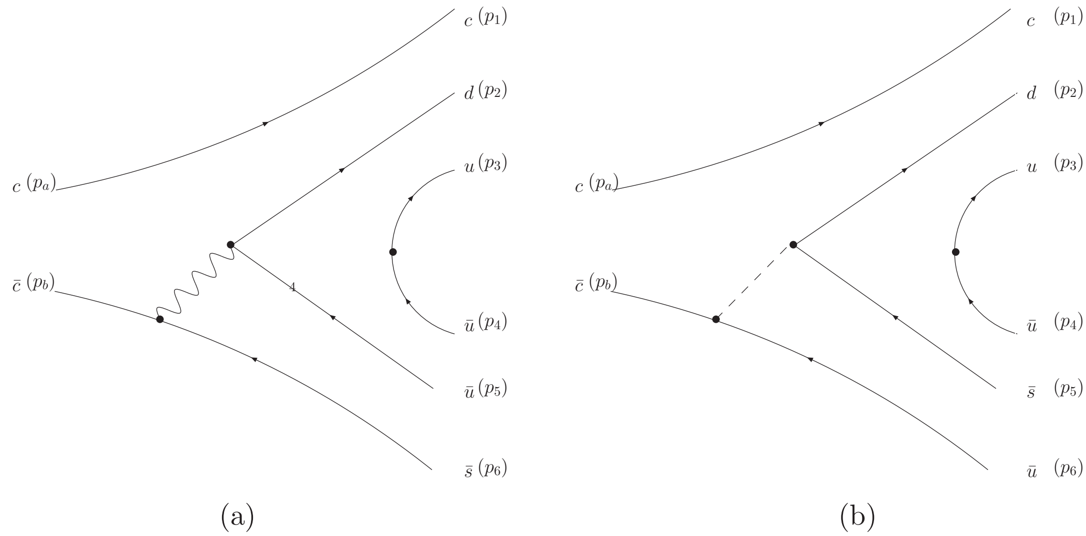

FIG. 1: The Feynman diagrams of $J/\psi \to \Lambda_c + \overline{\Sigma^+}$. (a) in SM; (b) beyond SM (the dotted line is the unparticle propagator)

The S-matrix element is

$$S_{fi} = \delta_{fi} - 2\pi\delta(E_f - E_i)\langle f|H_I|i\rangle, \tag{1}$$

and the Hamiltonian H_I which is responsible for the creation of quark-antiquark pair from the vacuum[7] is

$$\begin{aligned} H_I \;=\; & \int d\mathbf{p}_q d\mathbf{p}_{\bar{q}}[3\,\gamma\delta^3(\mathbf{p}_q + \mathbf{p}_{\bar{q}})\sum_m \langle 1,1;m,-m|0,0\rangle \\ & \times\mathcal{Y}_1^m(\mathbf{p}_q - \mathbf{p}_{\bar{q}})(\chi_1^{-m}\varphi_0\omega_{ij})]b_i^+(\mathbf{p}_q,s)d_j^+(\mathbf{p}_{\bar{q}},s'), \end{aligned} \tag{2}$$

where $\varphi_0 = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$ is an SU(3) flavor-singlet, ω_{ij} is a color-singlet, χ_1^{-m} for a spin-triplet, $\mathcal{Y}_1^m$ is a solid harmonic polynomial for the $L = 1$ orbital angular momentum and γ is a dimensionless constant representing the strength of the creation and generally it is a fully non-perturbative QCD factor and must be determined by fitting data. The S-matrix element can be expressed in terms of the amplitude M

$$S_{fi} = \delta_{fi} - 2\pi\delta^4(p_f - p_i)M. \tag{3}$$

For a two-body decay the width is

$$\Gamma = 2\pi\int d\mathbf{p}_B d\mathbf{p}_C\delta(m_A - E_B - E_C)\delta(\mathbf{p}_B + \mathbf{p}_C)|M|^2, \tag{4}$$

where A stands as the initial particle, B and C are the daughter hadrons. It is noted that the Bjorken-Drell convention is used.

C. Transition matrix element

Now we begin to evaluate the transition matrix element in the QPC model. First in terms of Eq.(1) we have

$$T_{fi} = -2\pi\delta(E_f - E_i)\langle\Lambda_c\overline{\Sigma^+}|H_W H_I|J/\psi\rangle, \tag{5}$$

where the hamiltonian H_W is responsible for the weak transition. The expression becomes

$$-i\frac{G_F}{\sqrt{2}}V_{cs}V_{ud}g^{\mu\nu}\bar{\psi}_c\gamma_\mu(1-\gamma_5)\psi_s\bar{\psi}_d\gamma_\nu(1-\gamma_5)\psi_u(2\pi)^4\delta^4(p_b - p_6 - p_5 - p_2), \tag{6}$$

and

$$H_W = -i\frac{G_F}{\sqrt{2}}V_{cs}V_{ud}g^{\mu\nu}\bar{\psi}_c\gamma_\mu(1-\gamma_5)\psi_s\bar{\psi}_d\gamma_\nu(1-\gamma_5)\psi_u\frac{(2\pi)^4}{m_\psi}\delta^3(p_b - p_6 - p_5 - p_2). \tag{7}$$

In terms of the wave functions listed in the Appendix we obtain

$$\begin{aligned} T_{fi} = \quad & -2\pi\delta(E_f - E_i)\frac{\delta_{ab}}{\sqrt{3}}\varphi_\psi\chi_\psi\frac{\varepsilon_{123}}{\sqrt{6}}\varphi_{\Lambda_c}\chi_{\Lambda_c}\frac{\varepsilon_{456}}{\sqrt{6}}\varphi_\Sigma\chi_\Sigma\int d\mathbf{p}_a d\mathbf{p}_b d\mathbf{p}_1 d\mathbf{p}_2 d\mathbf{p}_3 d\mathbf{p}_4 d\mathbf{p}_5 d\mathbf{p}_6 \\ & \langle L,S;M-m,m|J,M\rangle\Psi_J^{tot}(\mathbf{p}_a,\mathbf{p}_b)\Psi_{\Lambda_c}^{tot}(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)\Psi_\Sigma^{tot}(\mathbf{p}_4,\mathbf{p}_5,\mathbf{p}_6) \\ & \langle 0|b_1b_2b_3d_4d_5d_6\ H_W H_I\ b_a^\dagger d_b^\dagger|0\rangle \\ = \quad & -2\pi\delta(E_\psi - E_{\Lambda_c} - E_\Sigma)\mathcal{F}_c C_{fs}\int d\mathbf{p}_1 d\mathbf{p}_2 d\mathbf{p}_5 \psi_\psi\psi_{\Lambda_c}\psi_\Sigma\frac{1}{(2\pi)^6}\sqrt{\frac{m_c}{E_c}}\sqrt{\frac{m_s}{E_s}}\sqrt{\frac{m_u}{E_u}}\sqrt{\frac{m_d}{E_d}} \\ & \langle L,S;M-m,m|J,M\rangle(-i\frac{G_F}{\sqrt{2}}V_{cs}V_{ud}g^{\mu\nu})\frac{(2\pi)^4}{m_\psi}\bar{V}_c\gamma_\mu(1-\gamma_5)V_s\bar{U}_d\gamma_\nu(1-\gamma_5)V_u \\ & [3\gamma\Sigma_m\langle 1,1;m',-m'|0,0\rangle\mathcal{Y}_1^m(2\mathbf{p}_{\Lambda_c} - 2\mathbf{p}_1 - 2\mathbf{p}_2)]\delta^3(p_J - p_{\Lambda_c} - p_\Sigma), \end{aligned} \tag{8}$$

where $\mathcal{F}_c$ is a color-related factor and C_{fs} is a flavor-spin factor.

$$\begin{aligned} M = \quad & -\mathcal{F}_c C_{fs}\int d\mathbf{p}_1 d\mathbf{p}_2 d\mathbf{p}_5 \psi_J\psi_{\Lambda_c}\psi_\Sigma\frac{1}{(2\pi)^6}\sqrt{\frac{m_c}{E_c}}\sqrt{\frac{m_s}{E_s}}\sqrt{\frac{m_u}{E_u}}\sqrt{\frac{m_d}{E_d}} \\ & \langle L,S;M-m,m|J,M\rangle(-i\frac{G_F}{\sqrt{2}}V_{cs}V_{ud}g^{\mu\nu})\frac{(2\pi)^4}{m_\psi}\bar{V}_c\gamma_\mu(1-\gamma_5)V_s\bar{U}_d\gamma_\nu(1-\gamma_5)V_u \\ & [3\gamma\Sigma_m\langle 1,1;m',-m'|0,0\rangle\mathcal{Y}_1^m(2\mathbf{p}_{\Lambda_c} - 2\mathbf{p}_1 - 2\mathbf{p}_2)]. \end{aligned} \tag{9}$$

We need to emphasize that the expansion of the field operator ψ and $\bar{\psi}$ and the anti-commutation relations of the creation and annihilation operators need to follow the Bjorken-Drell convention.

III. $J/\psi \to \Lambda_c + \overline{\Sigma^+}$ BEYOND SM

Here we take the unparticle model as an examplefor the new physics beyond the SM. It is worth emphasizing that other new physics models beyond the SM may behave quite differently from the unparticle and their contributions to the mode may deviate by orders from that of unparticle. The corresponding Feynman diagrams are presented in Fig.1(b) where the intermediate agent is replaced by an unparticle. Unlike the W-boson, the unparticle is neutral and allows existence of a flavor-changing neutral curresnt, so $\bar{c}$ decays into $\bar{u}$. We below will exploit the cases with two kinds of unparticles i.e. scalar and vector unparticles.

For the scalar unparticle

$$\begin{aligned} M = \quad & -\mathcal{F}_c C_{fs} \int d\mathbf{p}_1 d\mathbf{p}_2 d\mathbf{p}_5 \psi_J \psi_{\Lambda_c} \psi_\Sigma \frac{1}{(2\pi)^6} \sqrt{\frac{m_c}{E_c}} \sqrt{\frac{m_s}{E_s}} \sqrt{\frac{m_u}{E_u}} \sqrt{\frac{m_d}{E_d}} \langle L, S; M-m, m|J, M\rangle \\ & \frac{C_S^{cu} C_S^{sd}}{(\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}})^2} \frac{A_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)} \frac{ip^\mu p^\nu}{(-p^2)^{2-d\mathcal{U}}} \frac{(2\pi)^4}{m_\psi} \bar{V}_c \gamma_\mu (1-\gamma_5) V_u \bar{U}_d \gamma_\mu (1-\gamma_5) V_s \\ & [3\gamma \Sigma_m \langle 1, 1; m', -m'|0, 0\rangle \mathcal{Y}_1^m (2\mathbf{p}_{\Lambda_c} - 2\mathbf{p}_1 - 2\mathbf{p}_2)], \end{aligned} \tag{10}$$

with p is the momentum of the unparticle and

$$A_{d_{\mathcal{U}}} = \frac{16\pi^{\frac{5}{2}}}{(2\pi)^{2d_{\mathcal{U}}}} \frac{\Gamma(d_{\mathcal{U}} + \frac{1}{2})}{\Gamma(d_{\mathcal{U}} - 1)\Gamma(2d_{\mathcal{U}})} \tag{11}$$

where $d_{\mathcal{U}}$ is the scale dimension[3].

For the vector unparticle

$$\begin{aligned} M = \quad & -\mathcal{F}_c C_{fs} \int d\mathbf{p}_1 d\mathbf{p}_2 d\mathbf{p}_5 \psi_J \psi_{\Lambda_c} \psi_\Sigma \frac{1}{(2\pi)^6} \sqrt{\frac{m_c}{E_c}} \sqrt{\frac{m_s}{E_s}} \sqrt{\frac{m_u}{E_u}} \sqrt{\frac{m_d}{E_d}} \langle L, S; M-m, m|J, M\rangle \\ & \frac{C_V^{cu} C_V^{sd}}{(\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1})^2} \frac{A_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)} \frac{i(p^\mu p^\nu/p^2 - g^{\mu\nu})}{(-p^2)^{2-d\mathcal{U}}} \frac{(2\pi)^4}{m_\psi} \bar{V}_c \gamma_\mu (1-\gamma_5) V_u \bar{U}_d \gamma_\mu (1-\gamma_5) V_s \\ & [3\gamma \Sigma_m \langle 1, 1; m', -m'|0, 0\rangle \mathcal{Y}_1^m (2\mathbf{p}_{\Lambda_c} - 2\mathbf{p}_1 - 2\mathbf{p}_2)]. \end{aligned} \tag{12}$$

IV. NUMERICAL RESULTS

Since it is impossible to integrate out the variables $\mathbf{p}_1$, $\mathbf{p}_2$ and $\mathbf{p}_5$ in M analytically we instead proceed the whole calculation in Eq.(5) numerically.

The input parameters $m_u = m_d = 0.33$GeV, $m_s = 0.50$GeV, $m_c = 1.8$GeV and $\gamma = 3$ are set in [7]. The parameter R in the wave function is corresponding to $1/\beta$ in [9] which can be fixed by fitting its decay constant. Instead, by means of the binding energy ΔE, we have $R^2_{J/\psi} \approx 3\text{GeV}^{-1}$ [7] which is close to the number obtained by fitting the decay constant. $R^2 \approx 6\text{GeV}^{-1}$[7] was determined for light baryon, thus we set $R^2_\Sigma = 6\text{GeV}^{-1}$ in our numerical computations. For Λ_c if the ud quarks can be regarded as a diquark $R^2_{\Lambda_c}$

should be equal to $R^2_{D_s}(i.e.\ \frac{1}{\beta^2_{D_s}})$ and β_{D_s} can be found in Ref. [9], approximately, but sufficiently accurate, we set $R^2_{\Lambda_c} = 4$ GeV^{-2}. In our calculation we suppose that the quarks which participate in the weak transition are approximately on shell. The parameters in the SM sector are $G_F = 1.166 \times 10^{-5}$, $V_{ud} = 0.974$, $V_{cs} = 0.957$[10]. With all the parameters we get $BR(J/\psi \to \Lambda_c + \overline{\Sigma^+}) = 1.90 \times 10^{-10}$. If we replace $\bar{s}$ by $\bar{u}$ in Fig.1 we obtain $BR(J/\psi \to \Lambda_c + \bar{p})$ as 1.77×10^{-11}.

For the unparticle scenario, according to the present literature, the relevant parameters are fixed as $\Lambda_{\mathcal{U}} = 1$TeV, $d_{\mathcal{U}} = 1.5$ $C^{cu}_S = 0.021$, C^{ds}_S, $C^{cu}_V = 0.0005$ according to Ref.[11], and we also set $C^{ds}_S = C^{cu}_S$ and $C^{ds}_V = C^{cu}_V$ in our calculations. If only the contribution from unparticle is considered, one has $BR(J/\psi \to \Lambda_c + \overline{\Sigma^+})$ to be 3.57×10^{-25} for scalar unparticle and it is 1.59×10^{-19} for vector unparticle. Because they are many orders of magnitude smaller than the contribution of the SM , the interference between the SM and unparticle contributions are negligible.

Thus it is found that the branching ratio of baryonic decays $J/\psi \to \Lambda_c + \overline{\Sigma^+}$ has the same order of magnitude with that of J/ψ decaying into a charmed meson plus something else[12].

V. CONCLUSION AND DISCUSSION

In this work we study the weak baryonic decay of J/ψ: $J/\psi \to \Lambda_c + \overline{\Sigma}^+$ in the SM and beyond. In the calculation we employ a phenomenological model i.e. the QPC model to deal with the quark-antiquark pair creation and for calculating the hadronic transition matrix elements we use the harmonic oscillator wavefunction to describe both the baryonic and mesonic bound states. The model parameters are fixed by fitting the available experimental data. The advantage is that we can reduce the model-dependence, while the disadvantage is that the errors in the data will be unavoidably brought into the theoretical predictions. As one has a better knowledge on the error in the data, on the other side however, the uncertainties are well controlled within a reasonable range, so the numerical results are trustworthy, at least at the order of magnitude, even though not very accurate.

The branching ratio of $J/\psi \to \Lambda_c + \overline{\Sigma^+}$ in the SM would reach the order of magnitude as about 10^{-10}, which is of the same order as that for mesonic decays of J/ψ. Such small branching fraction definitely cannot be observed by the present experimental facilities.

At first look, the unparticle scenario might provide a larger contribution to the decay mode because there does not exist a heavy weak scale M_W at its propagator. However, the the data of $D^0 - \bar{D}^0$ mixing[11], neutrino experiment[13] and lepton flavor violation [14] rigorously constrains the effective couplings of the unparticle and the SM particles, thus one cannot freely adjust anything at all. The resultant contribution of the unparticle to the decay width is many order of magnitude smaller than that of the SM. Therefore this decay mode cannot be a probe for the unparticle scenario which has been explored by many authors.

The large database of J/ψ which will be collected at BES III and the will-be super-flavor factory may reach the accuracy to realize the measurements on weak transitions. Just because of its significance such experiment is required to be carried out.

Indeed, if such weak processes were observed to be larger by orders than that we estimated above, it signifies existence of new physics beyond the SM or new mechanisms or new hadronic structure, but by our calculation, definitely not from the unparticle contribution.

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Appendix A: Notations

Here we list the wave functions for any meson and baryon

$$\begin{aligned}
|\psi\rangle &= \frac{\delta_{ab}}{\sqrt{3}}\varphi\chi\int d\mathbf{p}_a d\mathbf{p}_b \langle L,S;M-m,m|J,M\rangle \Psi^{tot}_{\psi}|c(p_a)\bar{c}(p_b)\rangle \\
|\Lambda_c\rangle &= \frac{\varepsilon_{123}}{\sqrt{6}}\varphi\chi\int d\mathbf{p}_1 d\mathbf{p}_2 \mathbf{p}_3 \Psi^{tot}_{\Lambda_c}|c(p_1)d(p_2)u(p_3)\rangle \\
|\Sigma\rangle &= \frac{\varepsilon_{456}}{\sqrt{6}}\varphi\chi\int d\mathbf{p}_4 d\mathbf{p}_5 \mathbf{p}_6 \Psi^{tot}_{\Sigma}|\bar{u}(p_4)\bar{u}(p_5)\bar{s}(p_6)\rangle,
\end{aligned} \tag{A1}$$

where $\Psi^{tot}_{\psi} = \delta(\mathbf{p}_a+\mathbf{p}_b-\mathbf{p}_\psi)\phi(\mathbf{p}_a-\frac{\mathbf{p}_\psi}{2},\mathbf{p}_b-\frac{\mathbf{p}_\psi}{2})$, $\Psi^{tot}_{\Lambda_c} = \delta(\mathbf{p}_1+\mathbf{p}_2+\mathbf{p}_3-\mathbf{p}_{\Lambda_c})\phi(\mathbf{p}_1-\frac{m_c}{m_c+m_u+m_d}\mathbf{p}_{\Lambda_c},\mathbf{p}_2-\frac{m_d}{m_c+m_u+m_d}\mathbf{p}_{\Lambda_c},\mathbf{p}_3-\frac{m_u}{m_c+m_u+m_d}\mathbf{p}_{\Lambda_c})$ and $\Psi^{tot}_{\Sigma} = \delta(\mathbf{p}_4+\mathbf{p}_5+\mathbf{p}_6-\mathbf{p}_\Sigma)\phi(\mathbf{p}_4-\frac{m_u}{2m_u+m_s}\mathbf{p}_\Sigma,\mathbf{p}_5-\frac{m_u}{2m_u+m_s}\mathbf{p}_\Sigma,\mathbf{p}_6-\frac{m_s}{2m_u+m_s}\mathbf{p}_\Sigma)$.

The spatial wave functions of the ground-state baryon and meson are

$$\phi(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3) = (\frac{3R_B^2}{\pi})^{3/2}\exp[-\frac{R_B^2}{6}\sum_{i,j}(\mathbf{p}_i-\mathbf{p}_j)^2];$$

$$\phi(\mathbf{p}_a,\mathbf{p}_b) = (\frac{R_M^2}{\pi})^{3/2}\exp[-\frac{R_M^2}{8}(\mathbf{p}_1-\mathbf{p}_2)^2].$$

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