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P_c in Molecular Picture

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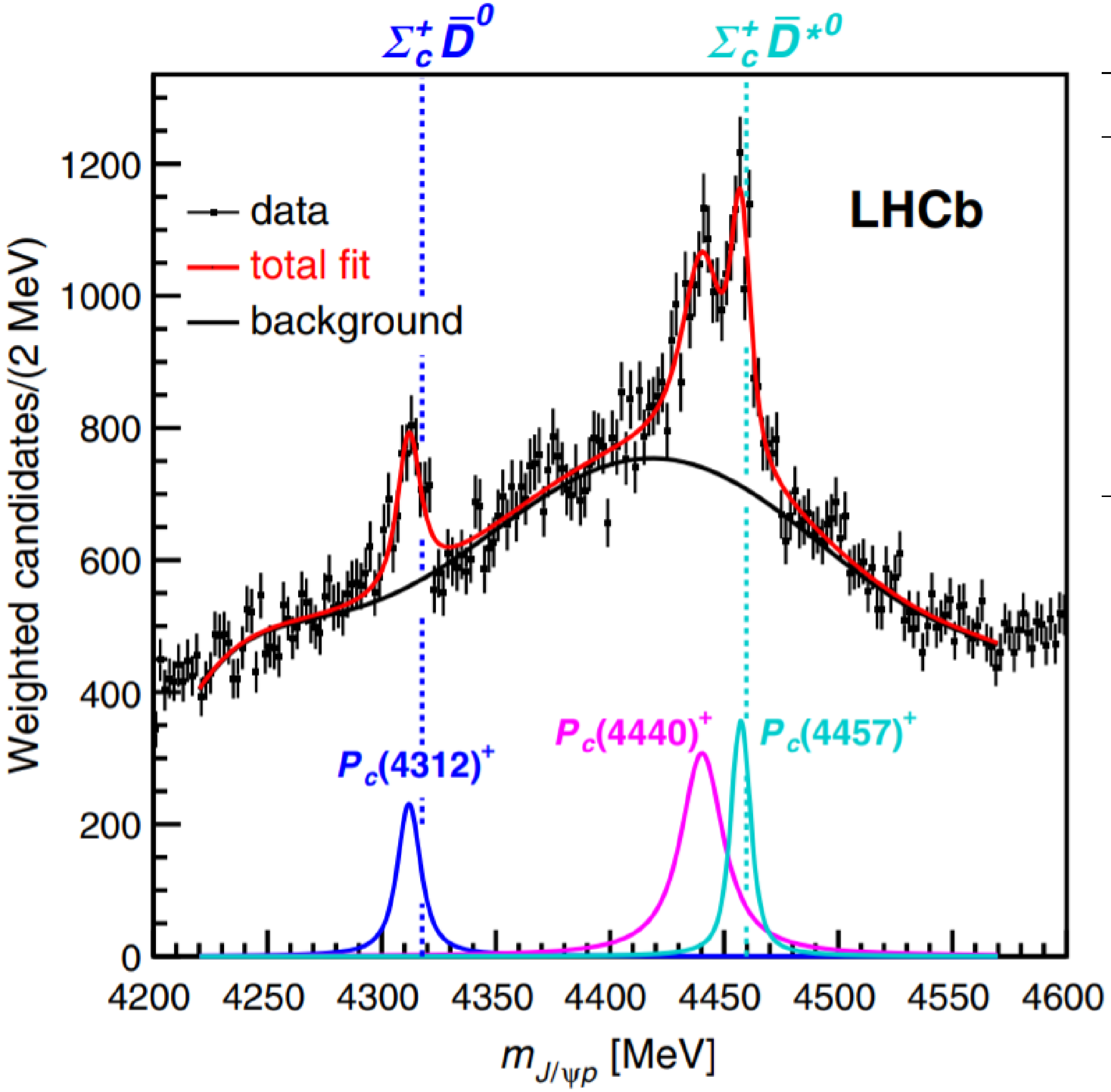
Hidden-charm pentaquark P_c



P_c states	Γ [MeV]	State	E [MeV]
$P_c(4312)$	$9.8 \pm 2.7^{+3.5}_{-4.5}$	$\Sigma_c^+ \bar{D}^0, \frac{1}{2}^-$	5
$P_c(4440)$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\Sigma_c^+ \bar{D}^{*0}, \frac{1}{2}^-$	20
$P_c(4457)$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\Sigma_c^+ \bar{D}^{*0}, \frac{3}{2}^-$	2

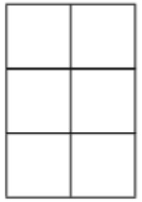
- $\Lambda_b^0 \rightarrow P_c K^- \rightarrow pJ/\psi K^-$
- Minimal quark content: $uudc\bar{c}$
- Quark model framework
- Strong decay study

[1] R. Aaij *et al.* (LHCb Collaboration) Phys. Rev. Lett. **122**, 222001

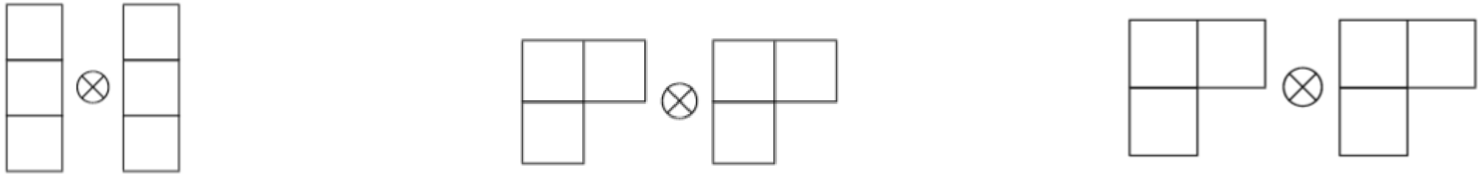
Wave function construction

- In this work, The hidden-charm pentaquark is in the molecule state of charmed baryon and anticharm meson, $[qqc][q\bar{c}]$.
- The wave function of the pentaquark follows:
  - ➢ The total wave function of the pentaquark should be color singlet.

$$\psi^{c}_{[222]}(qqcq\bar{c}) =$$



❖ There are 3 possible configurations of the baryon-meson molecule for the color singlet [222].



$$\psi^{c}_{[111]}(qqc) \otimes \psi^{c}_{[111]}(q\bar{c}) \qquad \psi^{c}_{[21]_\lambda}(qqc) \otimes \psi^{c}_{[21]}(q\bar{c}) \qquad \psi^{c}_{[21]_\rho}(qqc) \otimes \psi^{c}_{[21]}(q\bar{c})$$

❖ The explicit wave function can be calculated by

$$\psi^{c}_{[222]}(qqcq\bar{c}) = \psi^{c}_{[111]}(qqc) \otimes \psi^{c}_{[111]}(q\bar{c}) \qquad \psi^{c}_{[222]}(qqcq\bar{c}) = \frac{1}{\sqrt{8}}\sum_i \psi^{c}_{[21]_{j,i}}(qqc) \otimes \psi^{c}_{[21]_i}(q\bar{c})$$

➢ The wave function should be antisymmetric for the light quark separately by each cluster.

Baryon and meson clusters wave function

- The total wave function, which has four degrees of freedom, color ψ, spatial η, flavor ϕ, and spin χ, of the baryon cluster should be antisymmetric for the light quark q in the cluster.

$\psi_{[111]}(\phi_{[2]} \otimes \phi(c))\chi_{[3]}$
$\psi_{[111]}(\phi_{[2]} \otimes \phi(c))\chi_{[21]_\lambda}$
$\psi_{[111]}(\phi_{[11]} \otimes \phi(c))\chi_{[21]_\rho}$
$\psi_{[21]_\lambda}(\phi_{[11]} \otimes \phi(c))\chi_{[3]}$
$\psi_{[21]_\lambda}(\phi_{[11]} \otimes \phi(c))\chi_{[21]_\lambda}$
$\psi_{[21]_\lambda}(\phi_{[2]} \otimes \phi(c))\chi_{[21]_\rho}$
$\psi_{[21]_\rho}(\phi_{[2]} \otimes \phi(c))\chi_{[3]}$
$\psi_{[21]_\rho}(\phi_{[2]} \otimes \phi(c))\chi_{[21]_\lambda}$
$\psi_{[21]_\rho}(\phi_{[11]} \otimes \phi(c))\chi_{[21]_\rho}$

The possible configurations for the baryon cluster in the ground state ($\eta_{[3]}(qqc)$).

$\psi_{[111]}\phi(q\bar{c})\chi_{[2]}$
$\psi_{[111]}\phi(q\bar{c})\chi_{[11]}$
$\psi_{[21]}\phi(q\bar{c})\chi_{[2]}$
$\psi_{[21]}\phi(q\bar{c})\chi_{[11]}$

The possible configurations for the meson cluster in the ground state ($\eta_{[2]}(q\bar{c})$).

Total wave function

Pentaquark configuration	$\Psi(q^2c)$	$\otimes$	$\Psi(q\bar{c})$	Isospin	Spin
$\Psi_{[111]_C[2]_F[3][2]_S}$	$\psi_{[111]}\phi_{[2]}\chi_{[3]}$	$\otimes$	$\psi_{[111]}\phi(q\bar{c})\chi_{[2]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{5}{2},\frac{3}{2},\frac{1}{2}$
$\Psi_{[111]_C[2]_F[3][11]_S}$	$\psi_{[111]}\phi_{[2]}\chi_{[3]}$	$\otimes$	$\psi_{[111]}\phi(q\bar{c})\chi_{[11]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{3}{2}$
$\Psi_{[111]_C[2]_F[21][2]_S}$	$\psi_{[111]}\phi_{[2]}\chi_{[21]_\lambda}$	$\otimes$	$\psi_{[111]}\phi(q\bar{c})\chi_{[2]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{3}{2},\frac{1}{2}$
$\Psi_{[111]_C[2]_F[21][11]_S}$	$\psi_{[111]}\phi_{[2]}\chi_{[21]_\lambda}$	$\otimes$	$\psi_{[111]}\phi(q\bar{c})\chi_{[11]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{1}{2}$
$\Psi_{[111]_C[11]_F[21][2]_S}$	$\psi_{[111]}\phi_{[11]}\chi_{[21]_\rho}$	$\otimes$	$\psi_{[111]}\phi(q\bar{c})\chi_{[2]}$	$\frac{1}{2}$	$\frac{3}{2},\frac{1}{2}$
$\Psi_{[111]_C[11]_F[21][11]_S}$	$\psi_{[111]}\phi_{[11]}\chi_{[21]_\rho}$	$\otimes$	$\psi_{[111]}\phi(q\bar{c})\chi_{[11]}$	$\frac{1}{2}$	$\frac{1}{2}$
$\Psi_{[21]^\lambda_C[2]_F[21]^\rho[2]_S}$	$\psi_{[21]_\lambda}\phi_{[2]}\chi_{[21]_\rho}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[2]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{3}{2},\frac{1}{2}$
$\Psi_{[21]^\lambda_C[2]_F[21]^\rho[11]_S}$	$\psi_{[21]_\lambda}\phi_{[2]}\chi_{[21]_\rho}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[11]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{1}{2}$
$\Psi_{[21]^\lambda_C[11]_F[3][2]_S}$	$\psi_{[21]_\lambda}\phi_{[11]}\chi_{[3]}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[2]}$	$\frac{1}{2}$	$\frac{5}{2},\frac{3}{2},\frac{1}{2}$
$\Psi_{[21]^\lambda_C[11]_F[3][11]_S}$	$\psi_{[21]_\lambda}\phi_{[11]}\chi_{[3]}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[11]}$	$\frac{1}{2}$	$\frac{3}{2}$
$\Psi_{[21]^\lambda_C[11]_F[21]^\lambda[2]_S}$	$\psi_{[21]_\lambda}\phi_{[11]}\chi_{[21]_\lambda}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[2]}$	$\frac{1}{2}$	$\frac{3}{2},\frac{1}{2}$
$\Psi_{[21]^\lambda_C[11]_F[21]^\lambda[11]_S}$	$\psi_{[21]_\lambda}\phi_{[11]}\chi_{[21]_\lambda}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[11]}$	$\frac{1}{2}$	$\frac{1}{2}$
$\Psi_{[21]^\rho_C[2]_F[3][2]_S}$	$\psi_{[21]_\rho}\phi_{[2]}\chi_{[3]}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[2]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{5}{2},\frac{3}{2},\frac{1}{2}$
$\Psi_{[21]^\rho_C[2]_F[3][11]_S}$	$\psi_{[21]_\rho}\phi_{[2]}\chi_{[3]}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[11]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{3}{2}$
$\Psi_{[21]^\rho_C[2]_F[21]^\lambda[2]_S}$	$\psi_{[21]_\rho}\phi_{[2]}\chi_{[21]_\lambda}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[2]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{3}{2},\frac{1}{2}$
$\Psi_{[21]^\rho_C[2]_F[21]^\lambda[11]_S}$	$\psi_{[21]_\rho}\phi_{[2]}\chi_{[21]_\lambda}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[11]}$	$\frac{3}{2},\frac{1}{2}$	$\frac{1}{2}$
$\Psi_{[21]^\rho_C[11]_F[21]^\rho[2]_S}$	$\psi_{[21]_\rho}\phi_{[11]}\chi_{[21]_\rho}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[2]}$	$\frac{1}{2}$	$\frac{3}{2},\frac{1}{2}$
$\Psi_{[21]^\rho_C[11]_F[21]^\rho[11]_S}$	$\psi_{[21]_\rho}\phi_{[11]}\chi_{[21]_\rho}$	$\otimes$	$\psi_{[21]}\phi(q\bar{c})\chi_{[11]}$	$\frac{1}{2}$	$\frac{1}{2}$

Strong decay study

- The decay width formula for two-body decay, factorizing by the transition amplitudes of the spatial part and color-spin-flavor part, is given by

$$\Gamma_{p_c\to ij} = \frac{2\pi E_i E_j}{M_{P_c}} f(p^2)|\gamma_{CSF}|^2.$$

p is the center-of-mass momentum, $E_{i(j)}$ is the energy of the final particle i.

- $f(p^2)$ is the kinematic phase space factor stemming from the transition amplitude of the spatial part.
- To reduce the model dependence, we apply a phenomenological form for the phase factor from [2],

$$f(m_i, m_j, \sqrt{s}) = p \cdot Cexp\left(-A(s - s_{ij})^{\frac{1}{2}}\right).$$

C and A are constant, assuming to be equal for all decay channels, which $A = -1.2\ GeV^{-1}$, and $s_{ij} = (m_i + m_j)^{1/2}$.

- γ_{CSF} is the color-spin-flavor transition amplitude which is calculated from the overlap of the color-spin-flavor part of the initial and final states.

[2] J. Vandermeulen, Z.Phys.C 37 (1988) 563-567

Decay width ratios

- By using three P_c masses, we find the decay width for all the possible decay channels normalized by $\Gamma(\Psi^{J=3/2}_{[111]_C[2]_F[3][2]_S} \rightarrow pJ/\psi)$mode.
- Due to the result of three P_c are in the same magnitude, we present only the result from the $P_c(4457)$ for I = 1/2.

J	P_c configuration	$p\eta_c$	pJ/ψ	$\Sigma_c^*\bar{D}$	$\Sigma_c\bar{D}$	$\Lambda_c^+\bar{D}$	$\Lambda_c^+\bar{D}^*$
	$\Psi_{[111]_C[2]_F[3][2]_S}$		1				
	$\Psi_{[111]_C[2]_F[3][11]_S}$		0.59	69.63			
	$\Psi_{[111]_C[2]_F[21][2]_S}$		0.19				
$\frac{3}{2}$	$\Psi_{[111]_C[11]_F[21][2]_S}$		1.80				66.71
	$\Psi_{[21]^\rho_C[2]_F[3][2]_S}$		8.00				
	$\Psi_{[21]^\rho_C[2]_F[3][11]_S}$		4.80				
	$\Psi_{[21]^\rho_C[2]_F[21]^\lambda[2]_S}$		1.59				
	$\Psi_{[21]^\rho_C[11]_F[21]^\rho[2]_S}$		14.40				
	$\Psi_{[111]_C[2]_F[3][2]_S}$	1.07	0.39				
	$\Psi_{[111]_C[2]_F[21][2]_S}$	0.13	1.25				
	$\Psi_{[111]_C[2]_F[21][11]_S}$	0.40	0.14		67.51		
	$\Psi_{[111]_C[11]_F[21][2]_S}$	1.21	0.44				66.71
$\frac{1}{2}$	$\Psi_{[111]_C[11]_F[21][11]_S}$	0.40	1.34			53.94	
	$\Psi_{[21]^\rho_C[2]_F[3][2]_S}$	8.63	3.20				
	$\Psi_{[21]^\rho_C[2]_F[21]^\lambda[2]_S}$	1.09	10.00				
	$\Psi_{[21]^\rho_C[2]_F[21]^\lambda[11]_S}$	3.23	1.19				
	$\Psi_{[21]^\rho_C[11]_F[21]^\rho[2]_S}$	9.71	3.60				
	$\Psi_{[21]^\rho_C[11]_F[21]^\rho[11]_S}$	3.23	10.80				

Summary

- We study the hidden charm pentaquark in the molecule picture of charmed baryon and anticharm meson within the quark model framework.
- The wave functions are constructed by applying the group theory. We find all the possible ground-state configurations for the pentaquark in the molecule state totally 18 configurations, 47 states.
- The strong decay of each possible molecule states were investigated for all possible channels.
- Due to the color transition amplitude, the states with the color octet λ of the baryon cluster cannot strongly decay.
- The decay width ratios show that five open-charm decay modes are dominant over the hidden-charm decay channels. $p\eta_c$, $\Sigma_c\overline{D}$, and $\Lambda_c^+\overline{D}$ channels are open only J=1/2 while $\Sigma_c^*\overline{D}$ channel is open only J=3/2 except for $P_c(4312)$.
- We strongly suggest that the spin of P_c can be determined in experiment by investigating the $p\eta_c$ and the open-charm decay channels.

Appendix: Color octet wave function

$$\psi_{[21]_\lambda}(q^2c)_1 = \frac{1}{\sqrt{6}}(2rrg - rgr - grr),$$
$$\psi_{[21]_\lambda}(q^2c)_2 = \frac{1}{\sqrt{6}}(grg + rgg - 2ggr),$$
$$\psi_{[21]_\lambda}(q^2c)_3 = \frac{1}{\sqrt{6}}(2rrb - rbr - brr),$$
$$\psi_{[21]_\lambda}(q^2c)_4 = \frac{1}{\sqrt{12}}(2rgb + 2grb - gbr - rbg - brg - bgr),$$
$$\psi_{[21]_\lambda}(q^2c)_5 = \frac{1}{\sqrt{6}}(2ggb - gbg - bgg),$$
$$\psi_{[21]_\lambda}(q^2c)_6 = \frac{1}{\sqrt{6}}(brb + rbb - 2bbr),$$
$$\psi_{[21]_\lambda}(q^2c)_7 = \frac{1}{\sqrt{6}}(bgb + gbb - 2bbg),$$
$$\psi_{[21]_\lambda}(q^2c)_8 = \frac{1}{\sqrt{4}}(rbg + brg - bgr - gbr).$$

$$\psi_{[21]_\rho}(q^2c)_1 = \frac{1}{\sqrt{2}}(rgr - grr),$$
$$\psi_{[21]_\rho}(q^2c)_2 = \frac{1}{\sqrt{2}}(rgg - grg),$$
$$\psi_{[21]_\rho}(q^2c)_3 = \frac{1}{\sqrt{2}}(rbr - brr),$$
$$\psi_{[21]_\rho}(q^2c)_4 = \frac{1}{\sqrt{4}}(gbr + rng - brg - bgr$$
$$\psi_{[21]_\rho}(q^2c)_5 = \frac{1}{\sqrt{2}}(gbg - bgg),$$
$$\psi_{[21]_\rho}(q^2c)_6 = \frac{1}{\sqrt{2}}(rbb - brb),$$
$$\psi_{[21]_\rho}(q^2c)_7 = \frac{1}{\sqrt{2}}(gbb - bgb),$$
$$\psi_{[21]_\rho}(q^2c)_8 = \frac{1}{\sqrt{12}}(2rgb - 2grb - gbr + rbg - brg + bgr).$$

$$\psi_{[21]}(q\bar{c})_1 = b\bar{r},$$
$$\psi_{[21]}(q\bar{c})_2 = b\bar{g},$$
$$\psi_{[21]}(q\bar{c})_3 = -g\bar{r},$$
$$\psi_{[21]}(q\bar{c})_4 = \frac{1}{\sqrt{2}}(r\bar{r} - g\bar{g}),$$
$$\psi_{[21]}(q\bar{c})_5 = r\bar{g},$$
$$\psi_{[21]}(q\bar{c})_6 = -g\bar{b},$$
$$\psi_{[21]}(q\bar{c})_7 = r\bar{b},$$
$$\psi_{[21]}(q\bar{c})_8 = \frac{1}{\sqrt{6}}(2b\bar{b} - r\bar{r} - g\bar{g}).$$

Appendix: γ_{CSF}

I	j	P_c configuration	NJ/ψ	$N\eta_c$	$\Delta^+ J/\psi$	$\Delta^+\eta_c$	$\Sigma_c^*\bar{D}^*$	$\Sigma_c\bar{D}^*$	$\Lambda_c^+\bar{D}^*$	$\Sigma_c^*\bar{D}$	$\Sigma_c\bar{D}$	$\Lambda_c^+\bar{D}$
$\frac{3}{2}$	$\frac{5}{2}$	$\Psi_{[111]_C[2]_F[3][2]_S}$			$\frac{1}{3}$		1					
		$\Psi_{[21]_C^\rho[2]_F[3][2]_S}$			$\frac{2\sqrt{2}}{3}$							
$\frac{3}{2}$	$\frac{3}{2}$	$\Psi_{[111]_C[2]_F[3][2]_S}$			$\frac{1}{18}$	$\frac{1}{6}\sqrt{\frac{5}{3}}$	1					
		$\Psi_{[111]_C[2]_F[21][2]_S}$			$\frac{\sqrt{5}}{9}$	$-\frac{1}{3\sqrt{3}}$		1				
		$\Psi_{[111]_C[2]_F[3][11]_S}$			$\frac{1}{6}\sqrt{\frac{5}{3}}$	$\frac{1}{6}$				1		
		$\Psi_{[21]_C^\rho[2]_F[3][2]_S}$			$\frac{\sqrt{2}}{9}$	$\frac{1}{3}\sqrt{\frac{10}{3}}$						
		$\Psi_{[21]_C^\rho[2]_F[3][11]_S}$			$\frac{1}{3}\sqrt{\frac{10}{3}}$	$\frac{\sqrt{2}}{6}$						
		$\Psi_{[21]_C^\rho[2]_F[21][2]_S}$			$\frac{2\sqrt{10}}{9}$	$-\frac{2}{6}\sqrt{\frac{2}{3}}$						
$\frac{3}{2}$	$\frac{1}{2}$	$\Psi_{[111]_C[2]_F[3][2]_S}$			$-\frac{1}{9}$		1					
		$\Psi_{[111]_C[2]_F[21][2]_S}$			$\frac{\sqrt{2}}{9}$			1				
		$\Psi_{[111]_C[2]_F[21][11]_S}$			$\frac{1}{3}\sqrt{\frac{2}{3}}$						1	
		$\Psi_{[21]_C^\rho[2]_F[3][2]_S}$			$-\frac{2\sqrt{2}}{9}$							
		$\Psi_{[21]_C^\rho[2]_F[21][11]_S}$			$\frac{4}{3\sqrt{3}}$							
		$\Psi_{[21]_C^\rho[2]_F[21][2]_S}$			$\frac{4}{9}$							

Appendix: γ_{CSF}

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I	j	P_c configuration	NJ/ψ	$N\eta_c$	$\Delta^+ J/\psi$	$\Delta^+\eta_c$	$\Sigma_c^*\bar{D}^*$	$\Sigma_c\bar{D}^*$	$\Lambda_c^+\bar{D}^*$	$\Sigma_c^*\bar{D}$	$\Sigma_c\bar{D}$	$\Lambda_c^+\bar{D}$
$\frac{1}{2}$	$\frac{5}{2}$	$\Psi_{[111]_C[2]_F[3][2]_S}$					1					
$\frac{1}{2}$	$\frac{3}{2}$	$\Psi_{[111]_C[2]_F[3][2]_S}$	$\frac{1}{9}\sqrt{\frac{5}{2}}$				1					
		$\Psi_{[111]_C[2]_F[21][2]_S}$	$\frac{1}{9\sqrt{2}}$					1				
		$\Psi_{[111]_C[11]_F[21][2]_S}$	$\frac{1}{3\sqrt{2}}$						1			
		$\Psi_{[111]_C[2]_F[3][11]_S}$	$-\frac{1}{3\sqrt{6}}$							1		
		$\Psi_{[21]^\rho_C[2]_F[3][2]_S}$	$\frac{2\sqrt{5}}{9}$									
		$\Psi_{[21]^\rho_C[2]_F[3][11]_S}$	$-\frac{2}{3\sqrt{3}}$									
		$\Psi_{[21]^\rho_C[2]_F[21]^\lambda[2]_S}$	$\frac{2}{9}$									
		$\Psi_{[21]^\rho_C[11]_F[21]^\rho[2]_S}$	$\frac{2}{3}$									
$\frac{1}{2}$	$\frac{1}{2}$	$\Psi_{[111]_C[2]_F[3][2]_S}$	$\frac{1}{9}$	$\frac{1}{3\sqrt{3}}$			1					
		$\Psi_{[111]_C[2]_F[21][2]_S}$	$\frac{5}{18\sqrt{2}}$	$-\frac{1}{6\sqrt{6}}$				1				
		$\Psi_{[111]_C[11]_F[21][2]_S}$	$-\frac{1}{6\sqrt{2}}$	$\frac{1}{2\sqrt{6}}$					1			
		$\Psi_{[111]_C[2]_F[21][11]_S}$	$-\frac{1}{6\sqrt{6}}$	$\frac{1}{6\sqrt{2}}$							1	
		$\Psi_{[111]_C[11]_F[21][11]_S}$	$\frac{1}{2\sqrt{6}}$	$\frac{1}{6\sqrt{2}}$								1
		$\Psi_{[21]^\rho_C[2]_F[3][2]_S}$	$\frac{2\sqrt{2}}{9}$	$\frac{2}{3}\sqrt{\frac{2}{3}}$								
		$\Psi_{[21]^\rho_C[2]_F[21]^\lambda[2]_S}$	$\frac{5}{9}$	$-\frac{1}{3\sqrt{3}}$								
		$\Psi_{[21]^\rho_C[2]_F[21]^\lambda[11]_S}$	$-\frac{1}{3\sqrt{3}}$	$\frac{1}{3}$								
		$\Psi_{[21]^\rho_C[11]_F[21]^\rho[2]_S}$	$-\frac{1}{3}$	$\frac{1}{\sqrt{3}}$								
		$\Psi_{[21]^\rho_C[11]_F[21]^\rho[11]_S}$	$\frac{1}{\sqrt{3}}$	$\frac{1}{3}$								