Radiative transition of $\psi(2S) \to \chi_{c0}(1\mathcal{P}) + \gamma$ in light-front quark model

Anurag Yadav,* Satyajit Puhan, and Harleen Dahiya

Computational High Energy Physics Lab, Department of Physics,
Dr. B R Ambedkar National Institute of Technology, Jalandhar, Punjab, India, 144008

1. Introduction

Radiative transitions offer a clear probe of internal structure of quark-antiquark bound states via electromagnetic probes, with varied resolution. These transitions are vulnerable to relativistic effects, highlighting recent differences between NRQCD and experimental data [1]. Radiative transition between 1^{--} (vector) and 0^{++} (scalar) mesons via the emission of a photon is characterized as the electromagnetic transition (E1) transition. In this work, we have calculated the decay width and transition form factors (TFFs) of the $\psi(2S) \to \chi_{c0}(1\mathcal{P}) + \gamma$ E1 transition using light-front quark model (LFQM).

The paper is organized as follows. In Sec. 2, we have discussed the LFQM. The TFFs and decay width for the transition of $\psi(2S) \to \chi_{c0}(1\mathcal{P}) + \gamma$ have been explained in Sec. 3. The results of the present work has been explained in Sec. 4.

2. Light-front quark model

The minimal hadron Fock-state wave function based on light-front quantization in the form of quark-antiquark is given by [2]

$$|M^{nS(n\mathcal{P})}(P,J,J_z)\rangle = \sum_{\lambda_q,\lambda_{\bar{q}}} \int \frac{\mathrm{d}x\, \mathrm{d}^2\mathbf{k}_\perp}{\sqrt{x(1-x)}16\pi^3} \psi^{JJ_z}_{\lambda_q,\lambda_{\bar{q}}}(x,\mathbf{k}_\perp)\,|x,\mathbf{k}_\perp\rangle,$$

where $|M^{nS(n\mathcal{P})}(P,J,J_z)\rangle$ is the meson eigenstate with $P=(P^+,P^-,P_\perp)$ being the four-vector total momentum of the hadron and (J,J_z) is the total angular momentum. $nS(n\mathcal{P})$ stands for S-wave and $\mathcal{P}$-wave, $\mathbf{k}=(k^+,k^-,\mathbf{k}_\perp)$ is the momentum of the active quark and $x=\frac{k^+}{P^+}$ is the longitudinal momentum fraction carried by the active quark. Here $\lambda_{q(\bar{q})}$ is the helicity of quark (q) and anti-quark $(\bar{q})$.

The light-front wave function $\psi^{JJ_z}_{\lambda_q,\lambda_{\bar{q}}}$ for the pseudo-scalar and vector mesons is defined as follows

$$\psi^{JJ_z}_{\lambda_q,\lambda_{\bar{q}}}(x,\mathbf{k}_\perp) = \phi_{nS(n\mathcal{P})}(x,\mathbf{k}_\perp)\,\mathcal{X}^{JJ_z}_{\lambda_q\lambda_{\bar{q}}}(x,\mathbf{k}_\perp). \quad (1)$$

where $\phi_{nS(nP)}(x,\mathbf{k}_\perp)$ is the radial (orbital) wave function and $\mathcal{X}^{JJ_z}_{\lambda_q\lambda_{\bar{q}}}$ is the spin wave functions [3]. The $1\mathcal{P}$-wave radial wave function is taken as

$$\phi^{1\mathcal{P}}(x,) = 4\sqrt{2}\left(\frac{\pi}{\beta^2}\right)^{3/4} \sqrt{\frac{dk_z}{dx}}\,\frac{k_z}{\beta}\,\exp\left(-\frac{k_z^2+k_\perp^2}{2\beta^2}\right),$$

Similarly, for 2S radial wave form is given as

$$\phi^{2S}(x,) = 4\Big(\frac{\pi}{\beta^2}\Big)^{3/4}\sqrt{\frac{\partial k_z}{\partial x}}\exp\Big(-\frac{2^\delta}{2}\frac{k_z^2+k_\perp^2}{\beta^2}\Big) \Big(a_2'-b_2'\frac{k_z^2+k_\perp^2}{\beta^2}\Big).$$

Here $k_z=(x-1/2)M$ with bound state mass $M=\sqrt{\frac{k^2+m_c^2}{x(1-x)}}$ for charmonia $(c\bar{c})$. β and m_c are the harmonic scale operator and quark mass, having a value of 0.566 GeV and 1.4 GeV respectively [4].

3. Transition form factors

Transition form factor $E1(Q^2)$ for electric dipole decay of scalar meson $S \to V\gamma^*$(γ^* is virtual photon) is defined as

$$\langle M^{(1\mathcal{P})}(P',J,J_z)|J^+_{\text{em}}|M^{2S}(P,J,J_z)\rangle = ie\epsilon^{\mu\nu\rho\sigma}\epsilon_\nu(P,h)q_\rho P_\sigma E1(Q^2),$$

*Electronic address: anuragyadav1431905@gmail.com

our work	BLFQ [1]	MRK1'76	Dudek'09 [5]
25.353	21.953 $\pm$5.017	22.035 $\pm$7.897	25.902 $\pm$11.105
PDG [6]	CBAL'86	CLEO'04 [8]	BESIII'17[7]
28.781 $\pm$0.987	29.11 $\pm$2.879	27.053 $\pm$1.645	27.547 $\pm$1.233

TABLE I: Decay width of our LFQM result and other experimental data [1, 5–8] in unit of KeV

where $q = P - P'$ is the four momentum of the virtual photon, $\epsilon_\nu(P, h)$ is the polarization vector of the photon and helicity h. J^+ is the longitudinal charge density.

The decay width is found to be

$$\Gamma(S \to V\gamma) = \frac{\alpha}{3} E1^2(Q^2 = 0) k_\gamma^3,$$

where α is the strong coupling constant and $k_\gamma = (M_S^2 - M_V^2)/2M_S$. M_S and M_V are masses of $\psi(2S)$ and $\chi_{c0}(1\mathcal{P})$ respectively.

4. Results and Discussions

For numerical predictions of transition predictions, we need only two input parameters β and m_q, which are taken from Ref. [4]. The $E1(Q^2)$ TFFs for $\psi(2S) \to \chi_{c0}(1\mathcal{P}) + \gamma$ decay has been shown in Fig. 1 along with comparison with basic light-front quantization (BLFQ) [1] and lattice simulations results [5]. At $Q^2 = 0$, $E1(Q^2)$ is found to be 1.3 GeV^2, which is nearly equal to the particle data group (PDG) data [6], where as in case of BLFQ it was found to be 1 GeV^2. The behavior of $E1(Q^2)$ is found to be in good agreement with BLFQ result along with lattice simulations. The $E1(Q^2)$ decreases up to a energy scale $Q^2 = 1.8$ GeV^2, then increases with increase in Q^2.

The decay width $\psi(2S) \to \chi_{c0}(1\mathcal{P})$ of our calculations is found to be 25.353 KeV, which has been shown in Table I and compared with experimental results [6, 7] and lattice simulation results [1, 5, 6, 8]. Overall the LFQM results for the radiative decay $\psi(2S) \to \chi_{c0}(1\mathcal{P})$ is in good agreement with other model predictions, lattice simulations and experimental results.

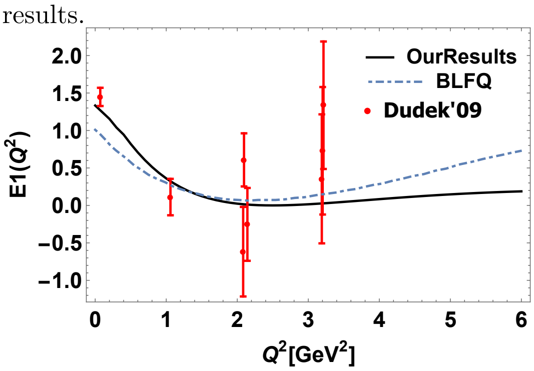

FIG. 1: Comparison of E1 radiative transition form factor of our work (LFQM) with BLFQ [1] and other lattice simulations [5].

Acknowledgments

H.D. would like to thank the Science and Engineering Research Board, Anusandhan-National Research Foundation, Government of India under the scheme SERB-POWER Fellow- ship (Ref No. SPF/2023/000116) for financial support.

References

[1] Z. Wang, *et al.*, Phys. Rev. D **109**, 3 (2024).

[2] S. Puhan, *et al.*, JHEP **02**, 075 (2024).

[3] R. Acharyya, *et al.*, [arXiv:2408.07715 [hep-ph]].

[4] Z. Q. Zhang, *et al.*, Eur. Phys. J. C **83**, 477 (2023).

[5] J. J. Dudek, *et al.*, Phys. Rev. D **79**, 094504 (2009).

[6] R. L. Workman *et al.* [Particle Data Group], PTEP **2022** (2022).

[7] M. Ablikim *et al.* [BESIII], Phys. Rev. D **96**, 032001 (2017).

[8] N. E. Adam, *et al.* [CLEO], Phys. Rev. Lett. **94**, 232002 (2005).