Two-photon decays of charmonium states

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The study of charmonium and bottomonium states, remain a cornerstone in understanding Quantum Chromodynamics (QCD) in the non-perturbative regime. These mesonic systems provide a unique testing ground for probing strong interactions at low energies, where confinement and gluonic dynamics dominate. Among the various decay processes of charmonium, the two-photon decays are particularly interesting as they offer a clean environment to explore the electromagnetic interaction in conjunction with QCD effects.

In this work, we focus on the two-photon decays of charmonium states such as the η_c and χ_{c0} which proceed through the well-known triangle quark-loop diagram. This diagram, involving a charm quark loop, plays a critical role in the decay process by mediating the interaction between the initial quark-antiquark bound state and the outgoing photon pairs. These decays provide valuable insight into the interplay between the strong and electromagnetic interactions, serving as a crucial probe of the internal structure of charmonium.

To analyze these decay processes, we employ the Bethe-Salpeter equation (BSE), a relativistic framework used to describe bound states in quantum field theory. By solving the BSE for the quark-antiquark bound state and incorporating the triangle quark-loop diagram, we aim to compute the decay amplitudes for the two-photon processes. This approach allows for a rigorous treatment of both the relativistic effects and the non-perturbative dynamics that are essential in charmonium physics.

Our BSE calculations are motivated by recent experimental advances in the high precision measurements of decays of charmonium states, particularly at facilities such as Belle, BABAR, and BESIII, which have advanced our understanding of the physics of charmonium. They have in turn contributed to improving theoretical models by providing updated measurements [1-4] of the decay widths and comparing these with predictions from QCD.

Bethe-Salpeter equation is firmly rooted in field theory, and is a useful non-perturbative tool for analysing hadrons as bound states of quarks and anti-quarks. We have recently been involved in calculations on the mass spectrum of ground and excited states of heavy-light mesons [5-6], leptonic decays, along with the radiative M1 and E1 decays of quarkonium. We have also been involved in high energy production processes [7] of charmonium states in electron-positron collisions at energies 4.0-10.6 GeV. Such processes have been observed at B-factories.

The two-photon decays of these states have been the subject of numerous studies aimed at further understanding the accuracy of theoretical models of the charmonium and bottomonium systems based on the available data.

The process, $M \to \gamma\gamma$ proceeds through the famous quark triangle diagrams shown in Fig. 1.

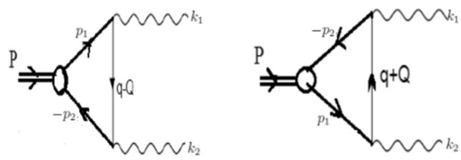

Fig.1: *Quark triangle diagrams contributing to two photon decays of a quarkonium. The second diagram is obtained from the first by reversing the arrows on internal fermion lines*

In this figure, the second diagram is obtained from the first one by reversing the directions of the internal fermion lines in the quark loop. Let,

$k_{1,2}$ and $\in_{1,2}$ be the momenta and polarization vectors of the two outgoing photons. Let, p_1 and p_2 be the momenta of constituent quark and anti-quark constituting the hadron with the total momentum $P = p_1 + p_2,$ and relative momentum q. We take Ψ(P, q) as the 4D hadron BS wave function of the decaying quarkonium. For sake of convenience, we introduce the relative momentum of the two outgoing photons: 2Q = k_1-k_2 In terms of P and Q, we can express the momenta of the outgoing photons as: $k_{1,2}$=$\frac{1}{2}$P ± Q. The amplitude for the process can be expressed as,

$$M_{fi} = \sqrt{3}\, e_Q^2 \int d^4 q \frac{d^4q}{(2\pi)^4} Tr[\psi(P,q) \notin_1 \times S_F(q-Q) \notin_2] + (1 \rightleftharpoons 2).$$

We work in the covariant Instantaneous Ansatz, where we resolve the internal hadron momentum, $q_\mu = (\hat{q}_{\mu,} M\sigma)$, where $\hat{q}_{\mu,}$ is the component of internal momentum transverse to the external hadron momentum, P, so that $\hat{q}.P = 0$, while $M\sigma$ (with $\sigma = \frac{q.P}{P^2} P_\mu$) is the component of internal momentum longitudinal to P, due to which the four-dimensional volume element, $d^4q = d^3\hat{q}$Mdσ. We first integrate over the longitudinal component, Mdσ.

In this work we have studied the two photon radiative decays of pseudoscalar mesons and scalar mesons, for which the 3D Salpeter wave functions are:

$$\psi_P(\hat{q}) = N_P[M + i\gamma.P + \frac{\gamma.\hat{q}\gamma.P}{m}]\gamma_5;$$

and

$$\psi_S(\hat{q}) = N_S\phi_S[M + i\frac{mM\gamma.\hat{q}}{\hat{q}^2} + \frac{2\gamma.P\gamma.\hat{q}}{m}].$$

For scalar quarkonium, we obtain the decay width,

$$\Gamma(S \to \gamma\gamma) = \frac{{F_S}^2}{32\pi M};$$

where the form factor,

$$F_S = \frac{16\alpha_{em}}{3\sqrt{3}\pi^2}\frac{m}{M} N_S \int \frac{d^3\hat{q}}{(2\pi)^3}\phi_S(\hat{q})$$

Similarly for pseudoscalar quarkonia, we obtain the decay width,

$$\Gamma(P \to \gamma\gamma) = \frac{{F_P}^2 M^3}{64\pi};$$

where the form factor,

$$F_P = \frac{32\sqrt{3}\pi\alpha_{em}}{M^2} N_P \int \frac{d^3\hat{q}}{(2\pi)^3}\phi_P(\hat{q}).$$

where N_S and N_P are the Bethe-Salpeter normalizers, evaluated through the current conservation condition. Our results for some of the decay widths are:

$\Gamma(\chi_{c0}(1P) \to \gamma\gamma) = 2.567$keV
(Exp.=2.341.5keV[4]),

$\Gamma(\chi_{c1}(2P) \to \gamma\gamma)$ =1.376k eV,

$\Gamma(\eta_c(1S) \to \gamma\gamma) = 6.450$keV
(Exp.=5.1±0.4 keV[4]),

$\Gamma(\eta_c(2S) \to \gamma\gamma) = 3.045$keV
(Exp.=2.1±0.6 keV[4]).

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