Leptonic, Photonic and gluonic decay of S-wave charmonium

Ajay Majethiya[1*], Rahulbhai Mistry[1], Kaushal Thakkar[2], Manan Shah[3]
[1]V.S. Patel College of Arts & Science, Bilimora Affiliated to VNSGU, Surat 395007, Gujarat, India.
2Department of Physics, Government College, Daman, U.T. of Dadra & Nagar Haveli and Daman & Diu, Daman-396210, India.
[3]Department of Physical Science, P.D. Patel Institute of Applied Science, Charotar University of Science and Technology, CHARUSAT, Changa 388421, Gujarat, India.
* Email: ajay.phy@gmail.com

1. Introduction

In 1974, the J/ψ particle was discovered experimentally [1], which is identify as first bound state of charm (c) quark and its anti-particle ($\bar{c}$)[2]. Theoretically, the study of spectroscopy and decay properties of bound states using non-relativistic quark model acquired a renewed interest due to the available experimental facilities like LHCb, Belle, BaBar, DELPHI, CLEO, etc. that have been continuously providing new and accurate information about the hadrons [3]. Study of decay properties of quarkonia ($Q\bar{Q}$) decays into leptons, photons or gluons is very useful for the production, identification of resonances, as well as to recognize conventional meson and multiquark structure [4,5].

In this present paper, the mass spectra and decay rate of leptonic, photonic and gluonic decays of charmonium state $c\bar{c}$ (both vector and scalar meson) are computed by using a quark-antiquark non-relativistic model by solving the Schrödinger equation using variational method.

2.Theoretical Approach

We have employed a non-relativistic Hamiltonian for quark-antiquark ($Q\bar{Q}$) bound states system is given by:

$$H_{Q\bar{Q}} = \frac{P^2}{2m} + V_{Q\bar{Q}}(r) \qquad (1)$$

Where r is the distance between quark and antidiquark and $m = \frac{m_Q m_{\bar{Q}}}{m_Q + m_{\bar{Q}}}$

To obtain masses of quarkonia, we solve the basic Schrödinger equation with quark-antiquark interaction potential [6].

$$V_{Q\bar{Q}}(r) = V_v + V_s = -\frac{\alpha_c}{r} + Ar^{\nu} \qquad (2)$$

Where $\alpha_c = \frac{4}{3}\alpha_s$ for quark-antiquark bound state system, A is confining strength and ν is varying from 0.1 to 2.0.

S wave Masses of the quark-antiquark system are given by:

$$M = m_Q + m_{\bar{Q}} + E_d + \langle V_{SS}(r)\rangle_{Q\bar{Q}} \qquad (3)$$

Here,$V_{SS}(r)$ is spin-spin interaction term is given by [7]:

$$V_{SS}(r) = \frac{8\pi\alpha_c}{3m^2}\left(\frac{\sigma}{\sqrt{\pi}}\right)^3 exp^{-\sigma^3 r^2} S_Q \cdot S_{\bar{Q}} \qquad (4)$$

Where, S_Q and $S_{\bar{Q}}$ are the spins of quark and antiquark of charmonium respectively and σ is a Gaussian function parameter.

The expectation value of $S_Q \cdot S_{\bar{Q}}$ is given by quantum mechanical formula:

$$\langle S_Q \cdot S_{\bar{Q}} \rangle = \langle \frac{1}{2}\left(S^2 - {S_Q}^2 - {S_{\bar{Q}}}^2\right) \rangle \qquad (7)$$

we have also computed decay rate of leptonic, photonic and gluonic decays;

1. Decay into leptons

The leptonic decay width of n^3S_1 state ($J^{PC} = 1^{--}$) annihilate into lepton pair with or without first order radiative QCD correction factor is given by [8,9]:

$$\Gamma(n^3S_1 \to e^+e^-) = \frac{4{e_Q}^2\alpha^2|R_{nl}(0)|^2}{{M_{nS}}^2}\left(1 - \frac{16\alpha_s}{3\pi}\right) \qquad (8)$$

M_{nS} is mass of the decaying quarkonium state.

2. Decay into photons

The annihilation decay rate of $c\bar{c}$ states into two or three photons with or without radiative QCD correction factor is given by [8,9]:

$$\Gamma(n^1S_0 \to \gamma\gamma) = \frac{3e_Q{}^4\alpha^2|R_{nl}(0)|^2}{M_{nS}{}^2}\left(1 - \frac{3.4\alpha_s}{\pi}\right) \quad (9)$$

$$\Gamma(n^1S_1 \to 3\gamma) = \frac{4(\pi^2-9)e_Q{}^6\alpha^3|R_{nl}(0)|^2}{3\pi M_{nS}{}^2} \times \left(1 - \frac{12.6\alpha_s}{\pi}\right) \quad (10)$$

3. Decay into gluons

The annihilation decay rate of $c\bar{c}$ states into two or three gluons as well as into gluon with photon with or without radiative QCD correction factor is given by [8,9]:

$$\Gamma(n^1S_0 \to gg) = \frac{2\alpha_s{}^2|R_{nl}(0)|^2}{3M_{nS}{}^2}\left(1 + \frac{4.4\alpha_s}{\pi}\right) \quad (11)$$

$$\Gamma(n^3S_1 \to 3g) = \frac{10(\pi^2-9)\alpha_s{}^3|R_{nl}(0)|^2}{81\pi M_{nS}{}^2} \times \left(1 - \frac{6.6\alpha_s}{\pi}\right) \quad (12)$$

$$\Gamma(n^3S_1 \to \gamma gg) = \frac{8(\pi^2-9)e_Q{}^2\alpha\alpha_s{}^2|R_{nl}(0)|^2}{9\pi M_{nS}{}^2} \times \left(1 - \frac{4.4\alpha_s}{\pi}\right) \quad (13)$$

3. Results and conclusion

Our calculated results for the decay rate of $c\bar{c}$ states into leptons, photons and gluons with and without radiative QCD correction factor for potential index ν varying from 0.1 to 2.0 are presented in Table 1 and 2.

From the calculated results of leptonic, photonic and gluonic decay rates we can conclude that our results for decay rates at potential index ν =1.0 with radiative QCD correction factor are in good agreement with other available experimental and theoretical result.

(*$\Gamma_{CF}$is decay rate with correction factor)

ν	$\Gamma(n^3S_1 \to e^+e^-)$ (KeV)		$\Gamma(n^1S_0 \to \gamma\gamma)$ (KeV)		$\Gamma(n^3S_1 \to 3\gamma)$ (KeV)	
	Γ	Γ_{CF}*	Γ	Γ_{CF}	Γ	Γ_{CF}
0.1	3.13	1.00	1.07	0.92	0.41	0.20
0.5	8.92	2.86	3.14	2.70	1.18	0.58
1.0	15.5	4.99	5.61	4.84	2.06	1.01
1.5	19.6	6.29	7.19	6.20	2.60	1.27
2.0	23.5	3.35	8.74	7.53	3.12	1.53
[9]	8.33	3.62	10.3	6.62	4.41	3.94
Exp[3]	5.55		5.1		1.08	
[10]	4.947		10.380			

Table 1. Leptonic and Photonic decay rate of $C\bar{C}$ with and without correction factor.

ν	$\Gamma(n^1S_0 \to gg)$ (MeV)		$\Gamma(n^3S_1 \to 3g)$ (KeV)		$\Gamma(n^3S_1 \to \gamma gg)$ (KeV)	
	Γ	Γ_{CF}	Γ	Γ_{CF}	Γ	Γ_{CF}
0.1	3.61	5.64	72.4	11.5	4.23	1.86
0.5	10.6	16.5	206	32.9	12.0	5.29
1.0	18.9	29.6	359	57.3	20.9	9.22
1.5	24.3	37.9	452	72.3	26.4	11.6
2.0	29.5	46.0	543	86.7	31.7	13.9
[9]	24.2	36.5	442	269	31.0	8.99
Exp[3]	28.6		59.55		8.18	

Table 2 Gluonic decay rate of $c\bar{c}$ with or without correction factor.

References

[1] J.J. Aubert et. al., Phys. Rev. Lett **33**, 1404 (1974)

[2] G. Goldhaber et. al., Phys. Rev. Lett **37**, 255 (1976).

[3] P.A. Zyla et al. (Particle Data Group), prog. Theor.Exp. Phys.2020, 083C01(2020).

[4] W. Kwong, P.B. Mackenzie, R. Rosenfeld, J.L. Rosner, Phys. Rev. D **37**, 3210 (1988)

[5] W. Kwong, J.L. Rosner, Phys. Rev. D**38**, 279 (1988)

[6] E. Eichten et al., Phys. Rev. D **17**(11), 3090 (1978)

[7] H A Bethe and E E Salpether Quantum Mechanics of atoms of one-and two-electrons Springer (1957)

[8] W. Kwong, P.B. Mackenzie, R. Rosenfeld, J.L. Rosner, Phys. Rev. D **37**, 3210 (1988)

[9] Virendrasinh Kher and AjayKumar Rai, Chinese Physics C **42**, 08310

[10] Manan Shah, et. al., Phys. Rev. D **86**, 034015 (2012)