Status of Zc(4050), Y(4140) and Y(4360) states as mixed P wave states of charmonium

Tanvi Bhavsar[1],* Manan Shah[2],† and P.C.Vinodkumar[1]‡
[1]*Department of Physics, Sardar Patel University, Vallabh Vidyanagar-388 120, INDIA and*
[2]*P. D. Patel Institute of Applied Sciences, CHARUSAT, Changa-388 421, INDIA*

Introduction

During the past few years, many new charmonium states, such as X, Y, Z have been observed by BaBaR [1, 2], Belle [3] and CLEO [4] experiments.The Belle collaboration has reported the discovery of Y(4360)[5], $Z_c(4050)$ [6] and X(4350) [7]. The CDF Collaboration reported existence of a state called Y(4140) [8]. Present study is an attempt to identify some of these states as mixed P wave charmonia. Many of these states belongs to the P wave charmonia while quite a number of them qualified to be the mixed p-wave states[9].

Theoretical Methodology

We assume here that quark and anti quark inside the mesonic bound state is independently confined by a potential [10],

$$V(r) = \frac{1}{2}(1+\gamma_0)(\lambda r + V_0) \qquad (1)$$

Where λ is the strength of the confinement part of the potential. V_0 is a constant negative potential depth.

To get binding energy we have solved the two component (positive and negative energy) Dirac equation. Its solution can be written as [11],

$$\psi_{nlj}(r) = \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} \qquad (2)$$

where the positive and negative energy solutions are given by[12],

$$\psi_A^{(+)}(\vec{r}) = N_{nlj} \begin{pmatrix} \frac{ig(r)}{r} \\ \frac{(\sigma.\hat{r})f(r)}{r} \end{pmatrix} \mathcal{Y}_{ljm}(\hat{r}) \qquad (3)$$

$$\psi_B^{(-)}(\vec{r}) = N_{nlj} \begin{pmatrix} \frac{i(\sigma.\hat{r})f(r)}{r} \\ \frac{g(r)}{r} \end{pmatrix} (-1)^{j+m_j-l} \mathcal{Y}_{ljm}(\hat{r}) \qquad (4)$$

Where N_{nlj} is the normalization constant. f(r) and g(r) are radial solutions which can be obtained numerically to get the energy eigen values. The parameters are fixed to get the ground state masses of $c\bar{c}$. Apart from the i dependent energy a residual OGEP is assumed in our earlier study of B, B_s meson [10] is also been incorporated. The predicted P-wave masses are listed in table:1.

TABLE I: P-wave mass spectrum for $(c\bar{c})$ (in GeV).

nL	State	Present	Expermental [13]	[14]
1P	1^3P_2	3.53963	(3556.20 ± 0.0)	3.54
	1^3P_1	3.53977	(3510.66 ± 0.07)	3.50
	1^3P_0	3.50942	(3414.75 ± 0.31)	3.44
	1^1P_1	3.40365	(3525.42 ± 0.29)	3.51
2P	2^3P_2	3.86174	(3927.2 ± 2.6)	4.02
	2^3P_1	3.86418	-	3.99
	2^3P_0	3.84709	-	3.94
	2^1P_1	3.76070	-	3.99
3P	3^3P_2	4.14130	-	-
	3^3P_1	4.14364	-	-
	3^3P_0	4.12729	-	-
	3^1P_1	4.05232	-	-
4P	4^3P_2	4.38978	-	-
	4^3P_1	4.39203	-	-
	4^3P_0	4.37619	-	-
	4^1P_1	4.30912	-	-

*Electronic address: tanvibhavsar1992@yahoo.com
†Electronic address: mnshah09@gmail.com
‡Electronic address: p.c.vinodkumar@gmail.com

Mixed P wave states

The mixed P wave states can be expressed as [15]

$$|\alpha\rangle = \sqrt{\frac{2}{3}}|^3P_1\rangle + \sqrt{\frac{1}{3}}|^1P_1\rangle \quad (5)$$

$$|\beta\rangle = -\sqrt{\frac{1}{3}}|^3P_1\rangle + \sqrt{\frac{2}{3}}|^1P_1\rangle \quad (6)$$

Where,$|\alpha\rangle$ $|\beta\rangle$ are states having same parity. We can write the masses of these states in terms of the predicted masses of the pure P wave states ($^3P_1$ and $^1P_1$) as [15]:

$$M(|\alpha\rangle) = \frac{2}{3}M(^3P_1) + \frac{1}{3}M(^1P_1) \quad (7)$$

$$M(|\beta\rangle) = \frac{2}{3}M(^1P_1) + \frac{1}{3}M(^3P_1) \quad (8)$$

TABLE II: Mixing of p wave

Exp. state	Mixed state configuration	Present
$Z_c(4050)$	3^3P_1 and 3^1P_1	4.082
Y(4140)	3^3P_1 and 3^1P_1	4.1130
Y(4360)	4^3P_1 and 4^1P_1	4.3643

Result and discussion

The predicted P-wave masses of charmonia are in very good agreement with experimental [13] results as given in Table I. We have also computed the masses of selected mixed P wave states and the results are given in table II. According to the results tabulated in table:2, we assign Y(4360) as a mixed state of 4^3P_1 and 4^1P_1 with a mixing angle of 35.26°, Y(4140) as a mixed state of 3^3P_1 and 3^1P_1 with a mixing angle of 35.26°. While $Z_c(4050)$ is close to the mixed state 3^3P_1 and 3^1P_1 with a mixing angle 54.74°.

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