Radiative X(3872) decays in a charmonium-molecule hybrid model

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The $X(3872)$ was first observed in 2003 by Belle [1] and was confirmed by CDF, D0, *BABAR* and LHCb collaborations. The observed mass of the $X(3872)$ is (3871.68 ± 0.17) MeV, which is 0.16 MeV below the $D^0 D^{*0}$ threshold and the full width is less than 1.2 MeV. The quantum numbers of the $X(3872)$ are not determined yet, but the favored ones are $J^{PC} = 1^{++}$. The theoretical prediction of the mass of the corresponding charmonium state was about 80 MeV above the observed one and it is one of the main reason that the $X(3872)$ is considered as the exotic state. The hadronic decay patterns of the $X(3872)$ show the large isospin symmetry breaking and it is another evidence of the exoticness.

In order to understand the structure of the $X(3872)$, we have studied the $X(3872)$ in the picture of the $c\bar{c}$ charmonium coupling to the $D^0\bar{D}^{*0}$ and D^+D^{*-} molecular state [2]. The strengths of the couplings between the charmonium state and the hadronic molecular states are determined so as to reproduce the observed mass of the the $X(3872)$. The $D\bar{D}^*$ attraction is taken to be consistent with the observed $Z_b(10610)$ and $Z_b(10650)$ masses. The isospin symmetry breaking is introduced by the mass differences of the neutral and the charged D mesons. The obtained structure of the $X(3872)$ is that about 6% is $c\bar{c}$ charmonium, 69% is the isoscalar $D\bar{D}^*$ molecule and 26% is the isovector $D\bar{D}^*$ molecule, which explains many of the observed properties of the $X(3872)$, such as the isospin symmetry breaking, the production rate in the $p\bar{p}$ collision, a lack of the existence of the $\chi_{c1}(2P)$ peak predicted by the quark model, and the absence of the charged partner of the $X(3872)$.

Since radiative decays of the $X(3872)$ are important in understanding its nature, we have applied our approach to the radiative decays of the $X(3872)$. The experimental situation is as follows. In 2009, *BABAR* [3] studied the $X(3872) \to J/\psi\,\gamma$ and $X(3872) \to \psi'\,\gamma$ decays and reported the ratio of the branching fractions was

$$\frac{Br(X(3872) \to \psi'\gamma)}{Br(X(3872) \to J/\psi\gamma)} = 3.4 \pm 1.4\,. \tag{1}$$

On the other hand, Belle [4] obtained

$$\frac{Br(X(3872) \to \psi'\gamma)}{Br(X(3872) \to J/\psi\gamma)} < 2.1\,. \tag{2}$$

In these decays, the J/ψ is the ground state and the ψ' is its first radial excited state for the $J^{PC} = 1^{--}$ state, while the $\chi_{C1}(2P)$ is the radial edited state of the $\chi_{C1}(1P)$, which is the grand state of the $J^{PC} = 1^{++}$ charmonium. In our approach, the $X(3872)$ has the charmonium core of the $\chi_{C1}(2P)$ state. It seems to be natural that the matrix element of the E1 transition between the $\chi_{C1}(2P)$ and the ψ' is bigger than that between the $\chi_{C1}(2P)$ and the J/ψ. One, therefore, considers that the *BABAR* result is understandable if the $X(3872)$ has the $\chi_{C1}(2P)$ as the main charmonium component. However, if the $X(3872)$ includes not only the $\chi_{C1}(2P)$ state but also the $\chi_{C1}(1P)$ state as the charmonium core states, the situation may change much.

Here, we introduce the $\chi_{C1}(1P)$ state in addition to the $\chi_{C1}(2P)$ state as the charmonium core states and consider the coupling of these two states to the charged and neutral $D\bar{D}^*$ hadronic molecule states. As the first attempt, we neglect the $D\bar{D}^*$ attraction for simplicity. Then, we obtain

$$|X(3872)\rangle = 0.071\,|c\bar{c}(1P)\rangle - 0.326\,|c\bar{c}(2P)\rangle + 0.907\,|D^0\bar{D}^{*0}\rangle + 0228\,|D^+D^{*-}\rangle\,. \tag{3}$$

Using this wave function, we calculated the decay rates of the radiative $X(3872)$ decays. In this calculations, we used the results of the matrix elements of the E1 transition between $J^{PC} = 1^{--}$ and $J^{PC} = 1^{++}$ charmonium states in the quark potential model [5]. Our results are

$$\Gamma(X(3872) \to J/\psi\,\gamma) = 29.2\,\mathrm{keV}\,, \tag{4}$$

$$\Gamma(X(3872) \to \psi'\,\gamma) = 6.3\,\mathrm{keV}\,, \tag{5}$$

and the ratio is about 0.22, which is much smaller than the *BABAR* result. If the $\chi_{C1}(1P)$ component is neglected, the former result changes considerably.

$$\Gamma(X(3872) \to J/\psi\,\gamma) = 5.1\,\mathrm{keV}\,, \tag{6}$$

and the ratio is about 1.5. The couplings between the $D\bar{D}^*$ hadronic molecule states and the charmonium states have not been well determined in this approach. As one can see from above results, the ratio itself strongly depends on the size of the $\chi_{C1}(1P)$ component. Thus, the present result should be considered as qualitative one.

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