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Exploring the mass spectra and decay properties of all charm tetraquark

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For the diquark-antidiquark system, a non-relativistic model with relativistic corrections is applied in the sextet-antisextet configuration to determine the mass spectra of all charm tetraquarks. Using Cornell-like potential, the Schrödinger equation for the Charmonium meson is numerically solved to get the fitting parameters. The current study uses parameters derived from charmonium spectra to predict the mass spectra of all charm tetraquarks in sextet-antisextet configuration, reducing a four-body problem to a two-body problem. The potential decay channels are described using the framework of the quarkonium-like annihilation process.

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1. Introduction

Improvements in theoretical models and experimental methods have allowed for tremendous gains in the study of tetraquarks during the past decade [1–3]. One watershed point was the confirmation of the presence of tetraquarks by experiments at high-energy particle colliders. Two charm quarks and two charm antiquarks make up the tetraquark state known as X(6900), which was observed in 2020 by the CERN LHCb experiment [4]. The discovery of X (6900) upended preexisting theoretical frameworks and sparked a fresh curiosity for the dynamics of exotic hadrons. Advances in theory have followed the outcomes of experiments, with physicists creating models to explain tetraquark behavior and its part in strong force dynamics. Numerous theoretical frameworks have yielded significant understandings regarding the composition and characteristics of tetraquarks. Furthermore, tetraquark research now encompasses more than just conventional high-energy experiments. Various computational methods, including QCD Sum Rule [5], Lattice QCD [6], and potential phenomenology [7, 8], have provided different insights into the properties of these exotic particles. With the goal of providing a more thorough knowledge of tetraquark existence, these theoretical frameworks seek to close the gap between the strong force at the quark level and the observed properties of these particles. Particle physicists are intensively studying the production mechanisms, decay patterns, and implications of tetraquarks for our understanding of particle physics as their examination of the particle continues. The present work aims at studying the mass spectra of all charm tetraquarks in the configuration of sextet-antisextet. In our earlier research, we investigated tetraquarks in antitriplet-triplet configuration [9–15]. The mass spectra of the tetraquark are determined in this study by applying a Cornell-like potential with a first-order correction in mass. These results are then compared with those of different theoretical models and two-meson thresholds. The outline of the paper is as follows: Section 2 provides a description of the theoretical framework and mass spectra of the charmonium meson, diquark, and all charm tetraquark, following a brief introduction in Section 1. Section 3 presents the findings and comparisons for the particles.

2. Framework

In an all-heavy tetraquark, a non-relativistic model with a static potential is a reasonable approximation since each constituent quark's rest mass energy is far greater than its kinetic energy. The binding energy of each state is determined by solving the time-independent radial Schrodinger wave equation of the corresponding state given by,

$$\left[\frac{-1}{2\mu}\left(\frac{d^2}{dr^2}+\frac{2}{r}\frac{d}{dr}-\frac{L(L+1)^2}{r}\right)+V(r)\right]\psi(r)=E\psi(r) \tag{1}$$

where L and E denote the orbital quantum number and energy eigenvalue, respectively. The Cornell-like potential used in this work takes the form of the linear confinement potential and the coulombic potential given by,

$$V^{(0)}_{C+L}(r)=-\frac{k_s\alpha_s}{r}+br-\frac{C_FC_A}{4}\frac{\alpha_s^2}{r^2}\left(\frac{1}{m_{cc}}+\frac{1}{m_{\bar{c}\bar{c}}}\right), \tag{2}$$

where k_s is the color factor, α_s is the QCD running coupling constant, b is the string tension, m_{cc} is the diquark mass and $m_{\bar{c}\bar{c}}$ is the anti-diquark mass. The value of the color factor for the color-singlet state and the sextet-antisextet state is $-\frac{4}{3}$ and $\frac{1}{3}$, respectively. The third term of the potential is the relativistic mass correction term $V^1(r)$ obtained from the leading-order perturbation theory, where C_F and C_A are the Casimir charges of the fundamental and the adjoint representation, respectively. In the present work, the values of fitting parameters are $\alpha_s = 0.525, b = 0.148\ GeV^2$ and $m_c = 1.459\ GeV$. The values of k_s for sextet diquark/anti-diquark and sextet-antisextet tetraquark are $\frac{1}{3}$ and $-\frac{10}{3}$, respectively. Following the mass spectra, the decay properties of bound particles are very significant. For the present work, an annihilation model analogous to the quark-antiquark annihilation [16, 17] is employed to estimate possible decay widths via photonic and gluonic channels.

3. Result and Discussion

Table 1. Mass spectra of $cc\bar{c}\bar{c}$ Tetraquark with various quantum number (MeV).

State	J^{PC}	$\langle V^1(r)\rangle$	Mass	Threshold
1^1S_0	0^{++}	-9.28	5313.31	$\eta_c(1S)\ \eta_c(1S)$
2^1S_0	0^{++}	-3.95	6903.66	-
1^1P_1	1^{--}	-4.33	6739.05	-
2^1P_1	1^{--}	-3.06	7490.97	-
1^3P_0	0^{-+}	-4.94	6240.04	$\eta_c(1S)\ \chi_{c0}(1P)$
2^3P_0	0^{-+}	-3.06	7109.77	-
1^3P_1	1^{-+}	-4.94	6730.63	$\eta_c(1S)\ \chi_{c1}(1P)$
2^3P_1	1^{-+}	-3.06	7476.77	-
1^3P_2	2^{-+}	-4.94	6904.77	$\eta_c(1S)\ \chi_{c2}(1P)$
2^3P_2	2^{-+}	-3.06	7608.20	-

The masses for All Charm Tetraquark are generated in the $\mathbf{6} - \bar{\mathbf{6}}$ configuration. Since the sextet diquark is repulsive in nature, it does not materialize as a compact state, giving a comparablely lower ground state mass. As the attraction between $\mathbf{6}$ and $\bar{\mathbf{6}}$ diquark is only 1.7 times the $\bar{\mathbf{3}}$ and $\mathbf{3}$ diquark, excited states show higher mass than the $\bar{\mathbf{3}} - \mathbf{3}$ tetraquark. The decay width for the 2 photon decay channel is **2.34 keV** with QCD correction and **5.51 keV** without QCD correction. Similarly, the decay width for the 2 gluon decay channel is **57.78 MeV** with QCD correction and **32.06 MeV** without QCD correction. The computed masses exhibit comparable results to other models, offering valuable insights for upcoming experimental and theoretical investigations into tetraquarks and other exotic hadrons. The states 2^1S_0 and 1^3P_2 are excellent candidates for X(6900) resonance as they are within 5 MeV proximity of the state.

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