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Masses of Charmed and Bottom Tetraquarks in the Nonrelativistic Quark Model

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Abstract

Heavy tetraquark states are studied within the diquark-antidiquark picture in the framework of a simple constituent quark model. Considering hyperfine spin-isospin interaction, we predict the masses of the scalar diquarks and of the open and hidden charmed and bottom scalar tetraquarks. Our results indicate the scalar resonances $D_0^*(2400)$ and D_S (2632) have a sizable tetraquark amount in their wave function, while it turns out the scalar states $D_{S0}^*(2317)$and $X(3915)$should not be considered as being predominately diquark-antidiquark bound states.

The Model

As a four-body system, a tetraquark state is quite different from a conventional meson and we solve the problem in a two-step procedure: first, we use a quark–quark interaction Hamiltonian in order to obtain the mass of a constituent diquarks. Second, we regard the diquarks as point-like objects and use a diquark–antidiquark interaction Hamiltonian in order to obtain the tetraquark masses. The radial part of the diquarks wavefunction is determined by two-body Schrodinger equation

$$\left[\frac{d^2}{dx^2}+\frac{2}{x}\frac{d}{dx}-\frac{\gamma(\gamma+1)}{x^2}\right]\psi_\gamma(x)=-2m\left[E_\gamma-V(x)\right]\psi_\gamma(x)$$

Where $\psi_\gamma(x)$, E_γ, x and γ are the wave function, energy eigenvalues, distance between two quarks, and angular quantum number respectively. m is the reduced mass and V(x) is considered as a combination of the oscillating and coulombic terms :

$$V_{Conf}(x)=ax^2-c/x+\tau$$

Where a, c and τ are constant. In the ansatz we use the transformation

$$\psi_\gamma(x)=x^{-1}\varphi_\gamma(x),\qquad \varphi_\gamma(x)=\exp[-\frac{1}{2}\alpha x^2+\delta\ln x]$$

And α and δ are constant. Substituting new wave function in the Schrodinger equation we get

$$\alpha=\sqrt{2ma}=1/2m\omega^2,\qquad \delta=\gamma+1$$

And then the eigenfuction and eigenenergy of the system are obtained:

$$\psi_\gamma=N_\gamma x^\gamma\exp(-\frac{m\omega}{2}x^2),\qquad E_\gamma=(2\gamma+3)\frac{\omega}{2}-\frac{2mc^2}{(2\gamma+2)^2}.$$

Now by using the obtained wave function, the perturbative spin- and isospin-dependent energy can be computed and then the diquarks masses are obtained as

$$M_{diq}=M_{antidiq}=m_{q1}+m_{q2}+E_\gamma+<H_S>+<H_I>+<H_{SI}>$$

The hyperfine interaction is introduced as

$$H_S=A_S(1/\sqrt{\pi}\sigma_s)^3\exp(-x^2/\sigma_S^2)(s_1.s_2)$$

$$H_I=A_I(1/\sqrt{\pi}\sigma_I)^3\exp(-x^2/\sigma_I^2)(t_1.t_2)$$

$$H_{SI}=A_{SI}(1/\sqrt{\pi}\sigma_{SI})^3\exp(-x^2/\sigma_{SI}^2)(s_1.s_2)(t_1.t_2)$$

Now we consider the diquarks and anti-diquarks as point particles and repeat our solving method for two-body systems. The quark–antiquark potential and quark–quark potentials are related by $V_{q\bar{q}}=2V_{qq}$. Thus, taking into account the factor 2, we get $V_{Conf}(x)=2ax^2-2c/x+\tau$
For the scalar tetraquarks, the constituent particles have zero spin and therefore, we have

$$M_{Tetraq}=m_{diq}+m_{antidiq}+E_\gamma+<H_S>$$

Masses of open charmed and bottom tetraquarks (in MeV)

Tetraquark	Model	Ref.[4]	Ref. [5]	Exp [8,9]
$[cq\bar{q}\bar{q}]$	2464	2398	2399	2400
$[cq\bar{q}\bar{s}]$	2629	2618	2619	2317, 2632
$[cs\bar{q}\bar{s}]$	2789	2855	2753	
$[bq\bar{q}\bar{q}]$	5788	5763	5758	
$[bq\bar{q}\bar{s}]$	5929	5980	5997	
$[bs\bar{q}\bar{s}]$	6085	6217	6108	

Masses of double-hidden charmed and bottom tetraquarks

Tetraquark	Model	Ref.[4]	Ref. [4]	Ref. [2]
$[cq\bar{c}\bar{q}]$	3625	3807	3662	3812
$[cq\bar{c}\bar{s}]$	3768	4043	3862	3922
$[cs\bar{c}\bar{s}]$	3920	4268	4050	4051
$[bq\bar{b}\bar{s}]$	9670	10521	10044	10471
$[bs\bar{b}\bar{s}]$	9812	10747	10228	10572
$[bs\bar{b}\bar{s}]$	10001	10973	10412	10662

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