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ТЕТРАКВАРК КАК СВЯЗАННОЕ СОСТОЯНИЕ ЧАРМОНИЯ И ϕ-МЕЗОНА

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TETRAQUARKS AS A BOUND STATE OF CHARMONIUM AND ϕ-MESON

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Аннотация. В эксперименте LHCb в 2017 г. были обнаружены тетракварки — резонансные состояния с кварковым составом $s\bar{s}c\bar{c}$. В данной работе предлагается одна из возможных теоретических моделей, объясняющих возникновение таких состояний. В предложенной модели тетракварк представляет собой связанное состояние ϕ-мезона и чармония ψ(2*S*). Связывание происходит за счет хромоэлектрической поляризуемости $c\bar{c}$ — состояния в поле легкого мезона. Мы показываем, что тетракварк X(4274), наблюдаемый в распаде *J*/ψ–ϕ, хорошо описывается в рамках нашего формализма. Кроме того, мы делаем некоторые предсказания для новых тетракварковых состояний, поиск которых на эксперименте позволит проверить правомерность нашей теории в дальнейшем.

Ключевые слова: тетракварк, тензор энергии-импульса, хромоэлектрическая поляризуемость, адрон, пентакварк.

Abstract. Some resonance $s\bar{s}c\bar{c}$ states called tetraquarks were observed by LHCb in 2017. In this work we offer the one of the possible theoretical models explained their existence. We consider tetraquark as a bound state of φ meson and charmonium ψ(2*S*). Their binding is provided by the chromoelectric polarizability of the $c\bar{c}$ state and energy-momentum-tensor densities of the light hadron. We show that the tetraquark X(4274) observed in the *J*/ψ–ϕ spectrum is a good candidate for a bound state of ψ(2*S*) with a φ meson. We also make predictions which will allow testing our model.

Keywords: tetraquark, energy-momentum-tensor density, chromoelectric polarizability, hadron, pentaquark.

In the heavy quark limit, when the quarkonium size is much smaller than the size of the considered hadron, here ϕ, the effective interaction V_{eff} of an s-wave quarkonium with the ϕ-meson is described in terms of the quarkonium polarizability α and the energy-momentum tensor (EMT) densities of the ϕ-meson,

$$V_{\text{eff}}(r) = -\alpha \frac{4\pi}{b}\frac{g_c^2}{g_s^2}\left(vT_{00}(r) - 3p(r)\right),$$
$$v = 1 + \xi_s \frac{bg_c^2}{8\pi^2}. \tag{1}$$

Here $T_{00}(r)$ and $p(r)$ are the energy density and pressure [Polyakov, 2003] inside the ϕ-meson, which satisfy respectively

$$\int d^3r T_{00}(r) = m_\varphi,\ \int d^3r p(r) = 0, \tag{2}$$

and $b=(11/3N_c–2/3N_f)$ is the leading coefficient of the Gell-Mann-Low function, $g_c(g_s)$ is the strong coupling constant renormalized at the scale $\mu_c(\mu_s)$ associated with the heavy quarkonium (ϕ-meson). The parameter ξ_s denotes the fraction of the hadron energy carried by gluons at the scale μ_s [Novikov, Shifman, 1981]. It is approximately $g_c \approx g_s$ and $v\approx 1.5$ [Eides at al., 2016].

Very little is known about the EMT densities in the ϕ-meson. These densities are defined in terms of Fourier transforms of the EMT form factors $A(t)$ and $D(t)$ [Polyakov, 2003]. The energy density $T_{00}(r)$ and the pressure $p(r)$ entering the effective potential (1) are expressed in terms of form-factors $A(t)$ and $D(t)$ as follows:

$$T_{00}(r) = m_\phi \int \frac{d^3}{(2\pi)^3} e^{i\vec{p}\vec{r}} A\left(-\vec{p}^{\,2}\right),$$
$$p(r) = \frac{1}{6m_\phi}\frac{1}{r^2}\frac{d}{dr}\int \frac{d^3p}{(2\pi)^3} e^{i\vec{p}\vec{r}} D\left(-\vec{p}^{\,2}\right). \tag{3}$$

Obviously the normalization conditions (2) are satisfied automatically. Almost nothing is known about the *D*-terms of any meson [Polyakov, Schweitzer, 2018], except for the recent first phenomenological information on π^0 EMT form factors [Kumano, 2018]. But π^0 is a Goldstone boson, and its *D*-term does not need to be good guideline for a vector meson like ϕ.

In a very simple description one may assume simple generic forms, e.g., dipole and quadrupole Ansatz. We chose the quadrupole Ansatz for $D(t)$ in order to avoid a divergent pressure at the origin. However, we checked that our results are only moderately affected if one uses a singular at the origin pressure $p(r)$. In this case we describe the EMT densities in the ϕ-meson in terms of 3 parameters:

$$A(t) = \frac{1}{\left(1 - t/M_1^2\right)^2},\ D(t) = \frac{D}{\left(1 - t/M_2^2\right)^3}, \tag{4}$$

where M_1 is the dipole mass of $A(t)$, D is the value of the D term, and M_2 is the quadrupole mass of $D(t)$. The mass parameter M_1 can be related to the mean square radius of the energy density in the ϕ-meson as $r_E^2 = 12/M_1^2$ whereas the mass parameter M_2 is related to the mechanical mean square radius of the ϕ-meson as

$r^2_{mech} = 12/M_2^2$ [Polyakov, Schweitzer, 2018]. The radii and D term of the ϕ-meson are not known. Therefore here we shall assume wide ranges of values for these parameters (with i=E, mech):

$$0.05 < r_i^2 < 1\ fm^2,\ -15 < D < 0. \tag{5}$$

With the parameters in above mentioned intervals we obtain a set of effective potentials whose form varies considerably.

Let m_ψ, m_J, m_ϕ denote the masses of ψ(2S), J/ψ, ϕ-meson. The mass of the tetraquark state is defined as M=m_ψ+m_ϕ+E_{bind}. The binding energy E_{bind}<0 is obtained from solving the non-relativistic Schredinger equation with the effective potential defined in terms of the ψ(2S) chromoelectric polarizability α(2S) [Eides at al., 2016]:

$$\left(-\frac{\nabla^2}{2\mu_2} + V_{\text{eff}}(r) - E_{\text{bind}}\right)\Psi(\vec{r}) = 0\,, \tag{6}$$

where μ_2 is the reduced mass $\mu_2^{-1} = m_\psi^{-1} + m_\phi^{-1}$ of the bound particles and $\Psi(\vec{r})$ — the bound state wave function. The decay of the tetraquark into ϕ and J/ψ requires that M>m_J+m_ϕ and is governed by the same effective potential but rescaled, since now the α(2S→1S) polarizability is relevant. The formula for the decay width is given by [Eides at al., 2016]:

$$\Gamma = \frac{\mu_1 |\vec{q}|}{\pi}\left(\frac{\alpha(2S \to 1S)}{\alpha(2S)}\right)^2 \times \tag{7}$$
$$\times \left|\int d^3 r \Psi(\vec{r}) V_{\text{eff}}(r) e^{i\vec{q}\vec{r}}\right|^2,$$

where μ_1 is the reduced mass $\mu_1^{-1} = m_J^{-1} + m_\phi^{-1}$ of the decay products, and $|\vec{q}| = \sqrt{2\mu_1(M - m_J - m_\phi)}$ corresponds to the center-of-mass frame momentum of the decay products. The bound-state wave function $\Psi(\vec{r})$ corresponding to the binding energy E_{bind}=M–m_ψ–m_ϕ is normalized to unity, $\int d^3 r |\Psi(\vec{r})|^2 = 1$.

To evaluate the binding energy and width in E_{qs}. (6) and (7) we use the value α(2S)≈17 GeV^{-3}, which was shown to yield a robust description of the pentaquark state P_c(4450) interpreted as a N–ψ(2S) bound state under varying assumptions of different chiral models for nucleon EMT densities [Eides at al., 2016; Perevalova et al., 2016]. For the transitional chromoelectric polarizability we use |α(2S→1S)|≈2 GeV^{-3} from [Voloshin, 2008].

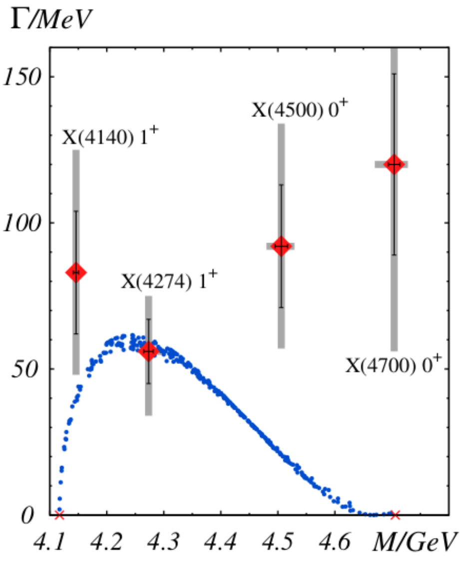
Not surprisingly, we obtain a wide range of masses M for the corresponding tetraquarks: practically every M in the allowed range m_J+m_ϕ<M<m_ψ+m_ϕ is realized for some choices of parameters M_1, M_2, D in the range (5). Also the results for Γ vary considerably.

The mass and width are functions Γ(M_1, M_2, D) and M(M_1, M_2, D) of parameters M_1, M_2, D which are varied randomly in the ranges (5). At first glance one would expect a scatter plot of Γ(M_1, M_2, D) versus M(M_1, M_2, D) to yield a random Γ–M distribution filling out the whole M–Γ plane. But surprisingly we find that the points lie more or less on one curve, see Fig. 1 [Panteleeva et al., 2019]. This is remarkable: even though we know nothing about the structure of the ϕ-meson, we can predict that M and Γ of candidate ψ(2S)–ϕ tetraquarks are systematically correlated. The crosses on the M-axis indicate the bounds m_J+m_ϕ<M<m_ψ+m_ϕ. For comparison we show the four tetraquarks in the J/ψ–ϕ resonance region with their statistical (thin lines) and systematic (shaded areas) uncertainties and spin parity assignments [Aaij et al., 2017]. The state X(4274) emerges as a candidate for the description as a hadrocharmonium. This method can be used to identify other possible hadroquarkonia.

Interestingly, the state X(4274) observed in the J/ψ–ϕ channel has a width of $\Gamma = 56 \pm 11^{+8}_{-11}$ MeV [Aaij et al., 2017] exactly in the range predicted by our scatter plot, see Fig. 1. The LHCb collaboration obtained for this state the quantum numbers J^{PC}=1^{++}. If one interprets this state as a ψ(2S)–ϕ bound state, one should expect two further nearly mass-degenerate resonances with spin 0 and 2 in this energy region. It would be interesting to check this hypothesis in partial wave analysis.

It is important to stress that adopting this interpretation for X(4274) implies that the X(4140), X(4500), X(4700) cannot be s-wave ψ(2S)–ϕ bound states. These states could be other hadrocharmonium states, possibly with l≥1, which might be possible in specific regions of the parameter space. Or their explanation may require different binding mechanisms. Addressing this question goes beyond the scope of this work.

Assuming that the state X(4274) is a hadrocharmonium allows us to gain some (very vague) information on the EMT densities of the ϕ-meson. The ψ(2S)–ϕ bound state with the mass around X(4274) appears for the following range of parameters; $r_E^2 \in [0.1,\ 0.55]\ fm^2$, $r^2_{\text{mech}} \in [0.08,\ 0.5]\ fm^2$, and D™ ™ [–5, 0]; the smaller radii correspond the larger values



The scatter plot of the decay width Γ(M_1, M_2, D) *vs* mass M(M_1, M_2, D) of tetraquarks obtained from varying the parameters M_1, M_2, D, which describe the unknown ϕ-meson EMT form factors (4), within a wide range of the values (5). In this plot 310 different points are shown of $|D|$. This is a very reasonable range of parameters for EMT densities in the ϕ-meson: for example, in the anti-de Sitter QCD model one finds $r_E^2 \in 0.21\ fm^2$ for the ρ-meson [Abidin, Carlson, 2008]. This approach would yield similar results for other vector mesons such as ϕ.

Other interesting questions concern whether also other ψ(2*S*)–ϕ resonances can be described as bound or resonant states in the hadrocharmonium picture, and whether hadroquarkonia with the heavier $\bar{b}b$ states can exist. The chromoelectric polarizabilities of bottomonia are smaller than for charmonia, and the corresponding V_{eff} is in general weaker. The formation of hidden-bottom tetraquarks in the hadrocharmonium picture may therefore be more difficult. But these interesting topics deserve dedicated studies and will be addressed elsewhere.

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