Possible 0^{-+} glueball candidate $X(1835)$

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The possibility of $X(1835)$ discovered by BESII as a 0^{-+} glueball is studied in this paper. The decay rates of $X(1835) \to p\bar{p}$, VV are associated with the gluon spin contents of proton and vector mesons, respectively. Estimations of the decay rates of $X(1835) \to VV$, γV, $\gamma\gamma$ and the cross sections of $\gamma\gamma \to X(1835) \to f$ and $h_1 + h_2 \to X(1835) + \ldots$ are presented. It predicts that as a glueball $X(1835)$ is unlikely to be produced in J/ψ hadronic decays but as a $p\bar{p}$ it is likely.

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I. INTRODUCTION

The BESII has reported a discovery of a new resonance $X(1835)$ in $J/\psi \to \gamma X$, $X \to \eta' \pi^+ \pi^-$ [1].

$$M = 1833.7 \pm 6.1 \pm 2.7 \text{ MeV},$$

$$\Gamma = 67.7 \pm 20.3 \pm 7.7 \text{ MeV},$$

$$BR(J/\psi \to \gamma X) BR(X \to \eta' \pi^+ \pi^-) = (2.2 \pm 0.4 \pm 0.4) 10^{-4}$$

are determined. A narrow enhancement near $2m_p$ in the invariant mass spectrum of $p\bar{p}$ of $J/\psi \to \gamma p\bar{p}$ decays has been reported by BES [2]. No similar structure is seen in $J/\psi \to \pi^0 p\bar{p}$. In the range of $M_{p\bar{p}} \leq 1.9$ GeV the angular distribution is consistent with production of a pseudoscalar or scalar meson in J/ψ radiative decays. If it is interpreted as a 0^{-+} resonance the mass and the width are determined to be

$$M = 1859^{+3}_{-10}(\text{stat})^{+5}_{-25}(\text{syst}) \text{ MeV}, \qquad \Gamma < 30 \text{ MeV}$$

at 90% level [2].

$$BR(J/\psi \to \gamma X) BR(X \to p\bar{p}) = (7.0 \pm 0.4^{+1.9}_{-0.8}) 10^{-5}.$$

is determined. In recent three talks [3] of BES for a 0^{-+} X the estimations $BR(J/\psi \to \gamma X) \sim (0.5 - 2) \times 10^{-3}$ and $BR(X \to p\bar{p}) \sim (4\text{–}14)\%$ are presented. $BR(X \to p\bar{p})$ is very large.

The masses of the two structures observed in both $\gamma\eta'\pi^+\pi^-$ and $\gamma p\bar{p}$ channels are overlap and 0^{-+} quantum number for the resonance in $\eta'\pi^+\pi^-$ channel is possible. A question arises if they are the same state. In Ref. [1] an argument is presented if the final state interaction is included in the fit of the $p\bar{p}$ mass spectrum, the width of the resonance observed in $\gamma p\bar{p}$ channel will become larger. Therefore, the X observed in both $\gamma p\bar{p}$ and $\gamma\eta'\pi^+\pi^-$ channels could be the same state and it is named as $X(1835)$ in Ref. [1]. Various possibilities of the nature of $X(1835)$, such as $p\bar{p}$ bound state, glueball, and others, are investigated [4]. So far, neither possibility is ruled out nor confirmed. In this paper the possibility of $X(1835)$ as a candidate of 0^{-+} glueball [4] is further investigated. This paper is organized as: Sec. II: One state and two decay modes; Sec. III: $J/\psi \to \gamma X$ and $J/\psi \to VX$; Sec. IV: $X \to K^* \bar{K}^*$; Sec. V: $\gamma\gamma \to X \to f$; Sec. VI: Other processes; Sec. VII: Quark components; Sec. VIII: Summary.

II. ONE STATE AND TWO DECAY MODES

The decay width of $X(1835)$ is determined in the $\eta'\pi^+\pi^-$ channel and the distribution of the decay width of $J/\psi \to \gamma p\bar{p}$ has been measured [2]. If $X(1835)$ is a 0^{-+} glueball, the first question is can the distribution of the decay width of $J/\psi \to \gamma p\bar{p}$ [2] be understood by using the decay width of $X(1835)$ determined in the $\eta'\pi^+\pi^-$ channel? The effective Lagrangians are constructed to study this problem

$$\mathcal{L}_{JX\gamma} = e g_{JX\gamma} \frac{1}{m_J} X \epsilon_{\mu\nu\alpha\beta} \partial^\mu J^\nu \partial^\alpha A^\beta, \tag{1}$$

$$\mathcal{L}_{Xg} = \frac{g_{Xg}}{m_X} X \epsilon^{\mu\nu\alpha\beta} F^i_{\mu\nu} F^i_{\alpha\beta}, \tag{2}$$

where $F^i_{\mu\nu}$ is the strength tensor of gluon fields. In $J/\psi \to \gamma X(1835)$ $X(1835)$ couples to gluons. Equation (2) is the effective Lagrangian of the coupling between $X(1835)$ and gluons. Using Eq. (1),

$$\Gamma(J/\psi \to \gamma X) = \frac{\alpha}{24} g^2_{JX\gamma} m_J \left(1 - \frac{q^2}{m_J^2}\right)^3 \tag{3}$$

is obtained, where q is the momentum of $X(1835)$. Based on the value of $BR(J/\psi \to \gamma X)$ [3], $g^2_{JX\gamma} = (0.18 - 0.74) \times 10^{-3}$ is estimated. A glueball can couple to the gluons of a hadron directly. The effective Lagrangian $\mathcal{L}_{Xg}$ is essential in determining the glueball nature of $X(1835)$. Using Eq. (2), it is obtained

$$\langle p\bar{p}|s|X\rangle = i(2\pi)^4 \delta(p - k_1 - k_2) \frac{1}{\sqrt{2m_X}} g_{Xg} \frac{1}{m_X} \times \langle p\bar{p}|F\tilde{F}|0\rangle, \tag{4}$$

where $F\tilde{F} = \epsilon^{\mu\nu\alpha\beta} F^i_{\mu\nu} F^i_{\alpha\beta}$. It is known that this quantity is related to the gluon spin operator a_μ [5]

$$F\tilde{F} = -2\partial_\mu a^\mu,$$
$$a_\mu = -\epsilon^{\mu\nu\alpha\beta}\left\{F^i_{\nu\alpha}A^i_\beta - \frac{g}{3}C_{ijk}A^i_\nu A^j_\alpha A^k_\beta\right\}, \tag{5}$$

$$\langle p\bar{p}|F\tilde{F}|0\rangle = -2i(k_1 + k_2)^\mu \langle p\bar{p}|a_\mu|0\rangle, \tag{6}$$

where A^i_μ is gluon field. $\langle p\bar{p}|a_\mu|0\rangle$ is the matrix element of the gluon spin operator in the timelike region. The matrix element of gluon spin content of a proton is the corresponding matrix element in the spacelike region and is expressed as [5]

$$\langle p|a_\mu|p\rangle = \Delta G\bar{u}\gamma_\mu\gamma_5 u, \tag{7}$$

where ΔG is the gluon spin content of proton in spacelike region. In the region of $X(1835)$-resonance the momenta of proton and antiproton produced in the decay of $X(1835)$ are very low. The matrix element of Eq. (6) can be written as

$$\langle p\bar{p}|F\tilde{F}|0\rangle = -4i\Delta G(q^2 > 0)m_N\bar{u}\gamma_5 v, \tag{8}$$

where $\Delta G(q^2 > 0)$ is the gluon spin content of proton in the timelike region. Its value might not be the same as the gluon spin content ΔG which is defined in spacelike region. In order to estimate the order of magnitude of $\Delta G(q^2 > 0)$ we argue that it is possible that these two quantities can be described by the same analytic function. It is called cross symmetry.

For the whole process the amplitude of $J/\psi \to \gamma X, X \to p\bar{p}$ is

$$\sim \frac{\langle p\bar{p}|F\tilde{F}|0\rangle}{q^2 - m_X^2 + i\sqrt{q^2}\Gamma_X},$$

where q is the momentum of $p\bar{p}$. In the spacelike region the expression becomes

$$\sim \frac{\langle p|F\tilde{F}|p\rangle}{q^2 - m_X^2}.$$

The cross symmetry is the analytic continuation between $\langle p\bar{p}|F\tilde{F}|0\rangle$ and $\langle p|F\tilde{F}|p\rangle$. The former is in timelike space and the later is spacelike. In a field theory the amplitude has poles and cuts and the remaining part is analytic. In this paper the approach of effective field theory is exploited and the pole and cut appear in the denominator and the the numerator is analytic. Taking the pion form factor as an example, in Ref. [6] the pion form factor is obtained by a chiral fields theory [7]

$$\frac{f_{\rho\pi\pi}(q^2)}{q^2 - m_\rho^2 + i\sqrt{q^2}\Gamma_\rho(q^2)},$$

where $f_{\rho\pi\pi}(q^2)$ is an analytic function of q^2 and obtained from the $\langle\pi\pi|j_\mu|0\rangle$ (j_μ is the electric current), $\Gamma_\rho(q^2)$ is the decay width of ρ meson. This form factor fits the data in both spacelike and timelike regions very well. In this theory [7] the cross symmetry between $\langle\pi\pi|j_\mu|0\rangle$ and $\langle\pi|j_\mu|\pi\rangle$ is proved.

The diagonal matrix elements of a_μ are gauge invariant. For nondiagonal matrix elements of a_μ there are other terms. However, the divergence of these terms is zero and they do not affect Eq. (8). ΔG is an important quantity in understanding the proton spin. There are very active experimental projects on measuring it. In Ref. [8] the following data are quoted:

$$\Delta G(1\ \mathrm{GeV}^2) = 0.99^{+1.17+0.41+1.43}_{-0.31-0.22-0.45}(\mathrm{SMC}),$$
$$\Delta G(5\ \mathrm{GeV}^2) = 1.6 \pm 1.1(E155), \tag{9}$$

the current data show ΔG is insensitive to q^2. In this paper when estimating the decay rates the dependence of ΔG on q^2 is ignored and $\Delta G(q^2 < 0) \approx \Delta G$.

$$\Gamma(X \to p\bar{p}) = \frac{2}{\pi\sqrt{q^2}} g^2_{Xg} m_N^2 (\Delta G)^2 \left(1 - \frac{4m_N^2}{q^2}\right)^{1/2} \tag{10}$$

is derived, where q is the momentum of $X(1835)$. Equations (3) and (10) lead to

$$\frac{d\Gamma}{dq^2}(J/\psi \to \gamma X, X \to p\bar{p}) = \frac{\sqrt{q^2}}{\pi}\frac{\Gamma(J/\psi \to \gamma X)\Gamma(X \to p\bar{p})}{(q^2 - m_X^2)^2 + q^2\Gamma_X^2}, \tag{11}$$

where $q = k_1 + k_2$, k_1, and k_2 are momenta of p and $\bar{p}$ respectively. BES has measured the distribution of the decay rates of $J/\psi \to \gamma p\bar{p}$ [2]. Choosing $\Gamma_X = 50$ MeV, Eq. (11) fits the data [2] well (Fig. 1) and the value of Γ_X is consistent with the one determined from $J/\psi \to \gamma\eta'\pi\pi$.

The glueball explanation of $X(1835)$ supports that the two structures found in both $\gamma p\bar{p}$ and $\gamma\eta'\pi\pi$ originate in one resonance state. From Fig. 1 it can be seen that outside of the resonance theory decreases faster than data. Besides the resonance there are other processes which contribute to $J/\psi \to \gamma p\bar{p}$. Study of these processes is beyond the scope

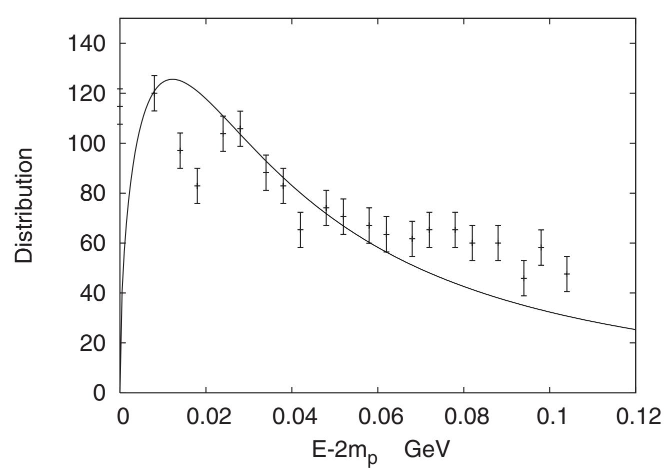

FIG. 1. Distribution of $J/\psi \to p\bar{p}$ with arbitrary unit.

of this paper. Using $BR(X \to p\bar{p})$ [3], it is estimated $g_{Xg}\Delta G = 0.27 \sim 0.51$. If taking $\Delta G \sim 1$, $g_{Xg} = 0.27 \sim 0.51$. Because $X(1835)$ is an isoscalar $\Gamma(J/\psi \to \gamma n\bar{n}) = \Gamma(J/\psi \to \gamma p\bar{p})$ is predicted. Equation (8) shows that the glueball $X(1835)$ is coupled to the gluons of proton directly and there is no QCD suppression. Therefore, large $BR(X \to p\bar{p})$ is understood qualitatively. Of course, if $X(1835)$ is a baryonium of $p\bar{p}$ the large decay width is very natural. Here we argue the large decay width is not a problem for the glueball explanation.

III. $J/\psi \to \gamma X$ AND $J/\psi \to VX$

In Ref. [9] it has been pointed out that $J/\psi \to \gamma + gg$, $gg \to$ hadrons provide an important search ground for glueballs. According to QCD, hadron productions in J/ψ decays originate in $J/\psi \to ggg$. Before studying the process $J/\psi \to \gamma X(1835)$ it is interesting to mention the production of a glueball in $J/\psi \to V(\rho, \omega, \phi)$ + hadron. According to the VMD [7],

$$\rho \to \frac{1}{2}egA, \qquad \omega \to \frac{1}{6}egA, \qquad \phi \to -\frac{\sqrt{2}}{6}egA, \quad (12)$$

where $g = 0.39$ is determined by fitting $\rho \to ee^+$ [7], there are another radiative decays $J/\psi \to V(\to \gamma)$ + hadrons. $J/\psi \to \gamma\pi^0$ is an example. In Ref. [10] $BR(J/\psi \to \gamma\pi^0)$ is via the VMD (12) calculated from the effective Lagrangian of $J/\psi \to \rho\pi$. $BR(J/\psi \to \gamma\pi^0)$ is small and theory agrees with data well. $J/\psi \to \gamma\sigma(f_0(600))$ is the second example. In Ref. [10], using an effective Lagrangian of $J/\psi \to \omega\sigma$ and the VMD (12), very small decay rate of $J/\psi \to \gamma\sigma$ is obtained. $\sigma(f_0(600))$ has not been found in J/ψ radiative decays [11]. Theory agrees with the data. Both π^0 and σ mesons are made of quarks. They have large branching ratios in the hadronic decays of J/ψ and small branching ratios in J/ψ radiative decays.

Very important information of the structure of η' meson is revealed from the productions of η' in J/ψ decays. The U(1) anomaly of η' [12] is known for a long time and η' meson is strongly coupled to gluons. The quark components of η' meson contribute only about $\frac{1}{3}$ of $m_{\eta'}$. It is known that the quark components dominate the structure of η meson. The data [13] show that $BR(J/\psi \to \omega(\phi)\eta) > BR(J/\psi \to \omega(\phi)\eta')$ and $BR(J/\psi \to \gamma\eta) < BR(J/\psi \to \gamma\eta')$. These results show that a meson which has substantial gluon component has larger $BR(J/\psi \to \gamma gg, gg \to$ meson) and small $BR(J/\psi \to V +$ meson). Assuming the gluon component of η' is responsible for $J/\psi \to \gamma + gg$, $gg \to \eta'$ decay, following ratio is obtained in Ref. [14] $\frac{BR(J/\psi \to \gamma\eta')}{BR(J/\psi \to \gamma\eta)} = 5.1$ which is consistent with data. In Ref. [15] two gluon components in η and η' are estimated. The branching ratio of $J/\psi \to V$ + glueball is suppressed at least by $O(\alpha_s^2)$.

The $BR(J/\psi \to \rho(\omega, \phi)p\bar{p})$ are measured to be $<3.1 \times 10^{-4}$, $(1.30 \pm 0.25) \times 10^{-3}$, $(4.5 \pm 1.5) \times 10^{-5}$ respectively [13]. If $J/\psi \to \gamma p\bar{p}$ is via the VMD obtained from $J/\psi \to Vp\bar{p}$, $BR(J/\psi \to \gamma p\bar{p})$ can be estimated from the $BR(J/\psi \to Vp\bar{p})$ and the large $BR(J/\psi \to \gamma p\bar{p}) = 7 \times 10^{-5}$ [2] cannot be obtained. Therefore, larger $BR(J/\psi \to \gamma p\bar{p})$ indicates that $J/\psi \to \gamma X(1835)$, $X(1835) \to p\bar{p}$ is obtained from $J/\psi \to \gamma gg$, $gg \to p\bar{p}$. On the other hand, hadronic productions of J/ψ are the processes of $J/\psi \to ggg$, $ggg \to q\bar{q}$ pairs $\to$ hadrons. Therefore if $X(1835)$ is a glueball, in which gluons are dominant, the production of $X(1835)$ in $J/\psi \to ggg$ is suppressed. Like η', $X(1835)$ contains substantial gluon component and the decay rate of $J/\psi \to V + X(1835)$, $X(1835) \to p\bar{p}$ is suppressed at least by $O(\alpha_s^2)$.

There is important gluon component in η' meson and the 2.2×10^{-4} branching ratio makes $J/\psi \to \gamma X(1835)$, $X(1835) \to \eta'\pi^+\pi^-$ a $J/\psi \to \gamma gg$, $gg \to \eta'\pi^+\pi^-$ decay. We predict that the branching ratios of $J/\psi \to \omega(\phi) + X(1835)$, $X(1835) \to \eta'\pi\pi$ should be much smaller too.

The two decay modes of $X(1835)$ ($p\bar{p}$ and $\eta'\pi^+\pi^-$) indicate that $X(1835)$ is strongly coupled to two gluons. A possible explanation is that $X(1835)$ is a 0^{-+} glueball. The study on glueballs has a long history. In Ref. [16] the spectrum of light glueballs and pseudoscalar glueball have been studied. The studies of scalar glueballs are presented in Ref. [17]. Lattice gauge calculations [18] predict the spectrum of glueballs. The quenched lattice gauge calculations predict higher mass for 0^{-+} glueball (2.3–2.6 GeV) [18]. However, the effects of quarks on these calculations are unknown. In Ref. [18] the QCD sum rule has been exploited to incorporate the quarks into account and much lower masses for the 0^{-+} glueball are obtained. The decay $J/\psi \to \gamma X(1835)$ is similar to $J/\psi \to \gamma\eta'$ in which only the gluon components of η' contribute [14]. Approximately

$$\frac{\Gamma(J/\psi \to \gamma X(1835))}{\Gamma(J/\psi \to \gamma\eta')} \sim \frac{1}{\sin^2\theta}\left(\frac{k_X}{k_{\eta'}}\right)^3, \qquad (13)$$

where $\sin\theta$ is defined in $|eta'\rangle = \cos\theta|q\bar{q}\rangle + \sin\theta|gg\rangle$, $k_X = \frac{m_J}{2}(1 - \frac{m_X^2}{m_J^2})$, and $k_{\eta'} = \frac{m_J}{2}(1 - \frac{m_{\eta'}^2}{m_J^2})$. Large $BR(J/\psi \to \gamma\eta')$ indicates that $\sin\theta$ is not small. Both $BR(J/\psi \to \gamma X(1835))$ and $BR(J/\psi \to \gamma\eta')$ are at the same order of magnitude ($\sim 10^{-3}$) which is consistent with the estimation made in Ref. [3]. The gluon components of η are very small, therefore, glueball $X(1835)$ predicts that $BR(X(1835) \to \eta'\pi\pi)$ is much greater than $BR(X(1835) \to \eta\pi\pi)$.

Besides η and η' there are other three 0^{-+} states: $\eta(1295)$, $\eta(1405)$, and $\eta(1475)$ [13]. Especially $BR(J/\psi \to \gamma\eta(1405/1475))$ is compatible with $BR(J/\psi \to \gamma\eta')$ and $BR(J/\psi \to \phi\eta(1405))$ is smaller [13]. In Ref. [19] it is argued that there is a 0^{-+} glueball candidate among them. It is interesting to measure $BR(X(1835) \to \eta(1295/1405/1475) + \pi\pi)$ to see whether a larger BR is among them. If any of them has larger such branching ratio it is a possible candidate of 0^{-+} glueball. If $\eta(1405)$ is a candidate of 0^{-+} glueball a larger $BR(X(1835) \to \eta(1405) + \pi\pi)$ should be expected.

IV. $X \to K^* \bar{K}^*$

Flavor independence of the decays is a very important property of a glueball. $J/\psi \to \gamma X(1835)$, $X(1835) \to \rho\rho$, $\omega\omega$, $K^*\bar{K}^*$ are other possible decay channels. A broad $\rho^0\rho^0$ enhancement at 1650 ± 200 MeV in $J/\psi \to \gamma\rho\rho$ with $\Gamma = 200 \pm 100$ MeV has been reported [20]. About 50% of the decays is due to a 0^- resonance and $BR(J/\psi \to \gamma X(1.5-1.9\ \text{GeV}, 0^-))BR(X \to \rho^0\rho^0) = (7.7 \pm 3.0)10^{-4}$ [21]. The 0^{-+} component appears strongly in BES data of $J/\psi \to \gamma + 2(\pi^+\pi^-)$ [22]. The $\omega\omega$ events reveal the similar structure. In Ref. [23] MARK III has reported that a dominant 0^{-+} component accounts for 55% of the data of $J/\psi \to \gamma K^*\bar{K}^*$. In this reaction BES [24] has found a broad 0^{-+} $K^*\bar{K}^*$ resonance with $M = 1800 \pm 100$ MeV and $\Gamma = 500 \pm 200$ MeV. In Ref. [25] the MARK III data of $J/\psi \to \gamma\eta\pi\pi$, $\rho\rho$, $\omega\omega$, $\phi\phi$, and $K^*\bar{K}^*$ have been analyzed and a very broad 0^- component in $K^*\bar{K}^*$ channel with mass of 1750–2190 MeV and a width of 1 GeV is found. In Ref. [26] the production of 2^{++} $q^2\bar{q}^2$ states in $J/\psi \to \gamma + VV$ has been studied. The resonance structures observed in $J/\psi \to \gamma + VV$ are more complicated. It is possible that 0^{-+} glueball $X(1835)$ is produced in $J/\psi \to \gamma + X(1835)$, $X(1835) \to VV$. The decays rates of $X(1835) \to VV$ can be calculated by using Lagrangian (2)

$$\langle VV|s|X\rangle = i(2\pi)^4\delta^4(p - k1 - k2)\frac{1}{\sqrt{2m_X}}\frac{g_{Xg}}{m_X} \times \langle VV|F\tilde{F}|0\rangle, \quad (14)$$
$$\langle VV|F\tilde{F}|0\rangle = 2ip^\mu\langle VV|a_\mu|0\rangle,$$

where p, k_1 and k_2 are momentum of X and V's, respectively,

$$\langle VV|a_\mu|0\rangle = \Delta G_V\langle VV|s_\mu^V|0\rangle, \quad (15)$$

where ΔG_V is the gluon spin content of vector meson in the timelike region and s_μ^V is the spin operator of vector meson

$$s_\mu^V = -\epsilon^{\mu\nu\alpha\beta}\left\{V^a_{\nu\alpha}V^a_\beta - \frac{g}{3}C_{abc}V^a_\nu V^b_\alpha V^c_\beta\right\},$$
$$V^a_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu + gc_{abc}V^b_\mu V^c_\nu, \quad (16)$$

where a is the index of flavor SU(3), $V^a_{\mu\nu}$ is the strength tensor of vector field V^a_μ. It is known that half of the energy of a meson is carried by gluons. Like proton, it is reasonable that gluon spin plays important role in understanding the spin of a vector meson. On the other hand, Eqs. (14) and (15) can be used to determined the timelike gluon spin content of vector meson. We use a chiral model of pseudoscalar, vector, and axial-vector mesons [7], which is very successful phenomenologically, to calculate the quark spin content of a vector meson, (for example, ρ meson),

$$\langle\rho^i|\bar{\psi}\gamma_\mu\gamma_5\psi|\rho^i\rangle = (\Delta u + \Delta d)\langle\rho^i|s_\mu|\rho^i\rangle,$$

where s_μ is the spin operator of vector meson (see below). The ρ meson vertex is defined as [7] $\frac{1}{g}\bar{\psi}\tau^i\gamma_\mu\psi\rho^i$, where g has been shown in Eq. (12) and the value of g determines $\Gamma_\rho = 150$ MeV. In the chiral limit g and f_π are the two parameters in this chiral theory. The calculation shows $\frac{1}{2} \times (\Delta u + \Delta d) = \frac{1}{2\pi^2 g^2} = 0.34$. $\Delta s = 0$ is obtained in the leading order in N_C expansion. The quark spin content of ρ meson is only $\frac{1}{3}$ of the total spin of ρ meson.

$$\langle\rho^i\rho^i|\bar{\psi}\gamma_\mu\gamma_5\psi|0\rangle = (\Delta u + \Delta d)\langle\rho^i\rho^i|s_\mu|0\rangle$$

is obtained too and cross symmetry is satisfied. The measurements of the decay rate of $X(1835) \to VV$ will provide important information of gluon spin content of vector meson. Of course if the gluon spin content is very small the quark operators produced by $F\tilde{F}$ must be taken into account and a suppression at $O(\alpha_s^2)$ for the decay rate of $X(1835) \to VV$ is the consequence and $BR(X(1835) \to VV)$ should be smaller. It is derived

$$\Gamma(X \to VV) = \frac{2f_V}{\pi}g^2_{Xg}(\Delta G_V)^2\sqrt{q^2}\left(1 - \frac{4m_V^2}{q^2}\right)^{3/2}, \quad (17)$$

where q is the momentum of X, $f_V = 1, \frac{1}{2}, \frac{1}{2}, 1, 1$ for $V = \rho^\pm$, ρ^0, ω, $K^{*\pm}$, K^{*0} respectively. The distribution of the decay $J/\psi \to \gamma X$, $X \to VV$ is obtained

$$\frac{d\Gamma}{dq^2}(J/\psi \to \gamma X, X \to VV) = \frac{\sqrt{q^2}}{\pi}\frac{\Gamma(J/\psi \to \gamma X)\Gamma(X \to VV)}{(q^2 - m_X^2)^2 + q^2\Gamma_X^2}. \quad (18)$$

In the region of the resonance of $X(1835)$ we obtain

$$BR(J/\psi \to \gamma + X, X \to \rho\rho) = 1.05 \times (0.13 - 1.89)10^{-3}\Delta G_V^2,$$
$$BR(J/\psi \to \gamma + X, X \to K^*\bar{K}^*) = 1.2 \times (0.13 - 1.89)10^{-4}\Delta G_V^2, \quad (19)$$

$$\frac{BR(J/\psi \to \gamma + X, X \to K^*\bar{K}^*)}{BR(J/\psi \to \gamma + X, X \to \rho\rho)} = 0.11. \quad (20)$$

The small ratio (20) is caused by the small phase space of $K^*\bar{K}^*$ channel. The ratio (20) is parameter independent and is the prediction of glueball $X(1835)$ whose decays should be flavor independent.

The branching ratio of $\omega\omega$ decay mode is $\frac{1}{3}$ of $\rho\rho$. If taking $\Delta G_V \sim 0.6$, the results are compatible with data [13] of $BR(J/\psi \to \gamma VV)$. Using the VMD (12), the decay rates of $J/\psi \to \gamma + X$, $X \to \gamma + V$ can be calculated

$$\frac{d\Gamma(J/\psi \to \gamma + X, X \to \gamma\rho)}{dq^2} = \frac{\sqrt{q^2}}{\pi}\frac{\Gamma(J/\psi \to \gamma X)\Gamma(X \to \gamma\rho)}{(q^2 - m_X^2)^2 + q^2\Gamma_X^2}, \tag{21}$$

$$\Gamma(X \to \gamma\rho) = 2\alpha g^2\sqrt{q^2}\left(1 - \frac{m_\rho^2}{q^2}\right)^3 g_{Xg}^2 \Delta G_V^2, \Gamma(X \to \gamma\omega) = \frac{2}{9}\Gamma(X \to \gamma\rho), \tag{22}$$

$$\Gamma(X \to \gamma\phi) = \frac{4}{9}\Gamma(X \to \gamma\rho)\frac{(1 - \frac{m_\phi^2}{q^2})^3}{(1 - \frac{m_\rho^2}{q^2})^3}. \tag{23}$$

Numerical results are

$$BR(J/\psi \to \gamma X, X \to \gamma\rho) = 0.88 \times (0.13 - 1.89)10^{-5}\Delta G_V^2, \tag{24}$$

$$\frac{BR(J/\psi \to \gamma X, X \to \gamma\rho)}{BR(J/\psi \to \gamma X, X \to \rho^0\rho^0)} = 0.83 \times 10^{-2}, \tag{25}$$

$$\frac{BR(J/\psi \to \gamma X, X \to \gamma\phi)}{BR(J/\psi \to \gamma X, X \to \gamma\rho^0)} = 0.11 \times 10^{-2}. \tag{26}$$

The ratios (25) and (26) are parameter independent and The measurements of the decay rates of $J/\psi \to \gamma + X$, $X \to K^*\bar{K}^*$ and $J/\psi \to \gamma + X, X \to \gamma\phi$ can test the flavor independence of glueball $X(1835)$.

V. $\gamma\gamma \to X \to f$

The 0^{-+} glueball $X(1835)$ can be produced by two photons. In Ref. [10] the VMD has been extended to J/ψ. Using the substitution $J_\mu \to e g_J A_\mu$, where $g_J = 0.0917$ is determined by fitting the decay rate of $J/\psi \to ee^+$,

$$\mathcal{L}^{(1)}_{X\gamma\gamma} = e^2 g_J \frac{g_{JX\gamma}}{m_J} X\epsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu \partial_\alpha A_\beta \tag{27}$$

is obtained. The second part of the effective Lagrangian of $X \to \gamma\gamma$ is obtained from $X \to VV$ by the substitutions (12)

$$\mathcal{L}^{(2)}(X \to \gamma\gamma) = \frac{4}{3}e^2 g^2 \frac{g_{Xg}}{m_X}\Delta G_V \epsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu \partial_\alpha A_\beta. \tag{28}$$

The cross section of $\gamma\gamma \to X \to f$ is found

$$\sigma(\gamma\gamma \to X \to f) = 8\pi\frac{\Gamma(X \to \gamma\gamma)\Gamma(X \to f)}{(q^2 - m_X^2)^2 + q^2\Gamma_X^2}, \tag{29}$$

where

$$\Gamma(X \to \gamma\gamma) = \pi\alpha^2\left\{g_J g_{XJ\gamma} + \frac{4}{3}\frac{m_J}{m_X}g^2 g_{Xg}\Delta G_V\right\}^2 \frac{m_X^3}{m_J^2} = 1.1(0.31 - 1.1)\ \text{keV}. \tag{30}$$

The calculation shows that the contribution of $\mathcal{L}^{(1)}$ can be ignored. Because of the gluon spin content of vector meson in $X \to \gamma\gamma$ there is no suppression at $O(\alpha_s^2)$, therefore, $\Gamma(X \to \gamma\gamma)$ is not narrow. As a matter of fact, $\sigma(\gamma\gamma \to p\bar{p})$ has been measured above 2 GeV [27]. $X(1835)$ can be via Primakov effects produced in photoproduction $\gamma p \to X(1835)p$. The cross section

$$\frac{d\sigma}{d\Omega} = \Gamma(X \to \gamma\gamma)\frac{8\alpha Z^2}{m_X^3}\frac{\beta^3 E^4}{Q^4}|F_{em}(Q)|^2 \sin^2\theta_m \tag{31}$$

can be found in Ref. [28]. The cross section of $X(1835)$ is at the same order of magnitude as π^0. On the other hand, $X(1835)$ can via a ρ exchange be produced in $\gamma p \to X(1835) + p$. At $q^2 \sim m_X^2$ the estimations $\sigma(\gamma\gamma \to X \to p\bar{p}) \sim pb$ and $\sigma(\gamma\gamma \to X \to \eta'\pi^+\pi^-) \sim 3\sigma(\gamma\gamma \to X \to p\bar{p})$ are made.

VI. OTHER PROCESSES

$X(1835)$ can be produced in the central region of hadron collisions by two gluons. In the parton model the cross section of the production of $X(1835)$ is written as

$$\sigma(h_1 + h_2 \to X + \ldots) = \int_{x_{1\,\min}}^1 \int_{x_{2\,\min}}^1 dx_1 dx_2 \{G_{g_1}^{h_1}(x_1)G_{g_2}^{h_2}(x_2) + G_{g_2}^{h_1}(x_1)G_{g_1}^{h_2}(x_2)\}\sigma(g_1 + g_2 \to X \to f), \tag{32}$$

where $G_g^h(x)$ is the gluon distribution function of hadron and $x_{1\,\min} = (m_1 + m_2)/S$, $x_{2\,\min} = (m_1 + m_2)/(x_1 S)$, m_1, m_2 are the masses of the two hadrons, $S = (p_1 + p_2)^2$,

$$\sigma(g_1 + g_2 \to f) = \frac{\pi}{2}\frac{\Gamma(X \to gg)\Gamma(X \to f)}{(q^2 - m_X^2)^2 + q^2\Gamma_X^2}, \quad q^2 = x_1 x_2 S, \tag{33}$$

$$\Gamma(X \to gg) = \frac{4}{\pi}g_{Xg}^2\sqrt{q^2}, \tag{34}$$

$$\frac{d\sigma(h_1 h_2 \to X \to f)}{dq^2} = \int_{x_{1\,\min}}^1 \frac{1}{x_1 S}dx_1\{G_{g_1}^{h_1}(x_1)G_{g_2}^{h_2}(x_2) + G_{g_2}^{h_1}(x_1)G_{g_1}^{h_2}(x_2)\} \times \sigma(g_1 g_2 \to X \to f). \tag{35}$$

The gluon distribution functions of nucleon and pion are chosen as

$$G_g^{\pi^+}(x) = 2(1 - x)^3/x, \quad G_g^p(x) = 2.62(1 + 3.5x)(1 - x)^{5.9}/x. \tag{36}$$

Using Eqs. (32)–(35), the cross sections of the production of $X(1835)$ in hadron collisions are estimated. As an example at $s = 750\ \mathrm{GeV}^2$ $\sigma(pp \to X + \ldots, X \to p\bar{p}) \sim 35\ \mu\mathrm{b}$, ($BR(X \to p\bar{p}) = 0.04$ is taken); $\sigma(pp \to X + \ldots, X \to \eta'\pi^+\pi^-) \sim 105\ \mu\mathrm{b}$, ($BR(X \to \eta'\pi^+\pi^-) = 0.12$ is taken). For πp collisions the two corresponding cross sections are $29\ \mu\mathrm{b}$ and $90\ \mu\mathrm{b}$ respectively.

$X(1835)$ can be produced in $ee^+ \to J/\psi + X(1835)$ [29]. In Ref. [30] the cross section of $ee^+ \to J/\psi +$ glueball(0^{++}) has been calculated to be $\sim fb$ at the energy 10.6 GeV. The process $\gamma^* \to (c\bar{c})(gg)$ involved in this process is the same as in $ee^+ \to J/\psi + X(1835)$. It is possible that the cross sections of both processes could be at the same order of magnitude, $\sigma(ee^+ \to J/\psi + X(1835)) \sim fb$ at the energy 10.6 GeV.

It is necessary to mention that the decay $B^+ \to p\bar{p}K^+$ has been reported by Belle [31] in 2002. The mass spectrum of $p\bar{p}$ has a wider distribution. However, as mentioned in Ref. [32] that $p\bar{p}$ mass spectrum is peaked toward low mass and for $M(p\bar{p}) < 2$ GeV $BR = (0.9^{+0.42}_{-0.35})10^{-6}$ which is larger than the BR in 2.0–2.2 GeV range. The structure of the mass spectrum of $p\bar{p}$ of $B^+ \to p\bar{p}K^+$ is more complicated than the one in $J/\psi \to \gamma p\bar{p}$ [2]. The process $B^+ \to K^+ + c\bar{c}$, $c\bar{c} \to gg$, $gg \to p\bar{p}$ is a possible contributor of $B^+ \to p\bar{p}K^+$. According to the study presented in this paper, the possibility of the production of $X(1835)$ in the decay $B^+ \to K^+X(1835)$, $X(1835) \to p\bar{p}$ cannot be ruled out. The measurements $B^+ \to K^+X(1835)$, $X(1835) \to \eta'\pi\pi$ are necessary to establish the production of $X(1835)$ in B decays. Using the data presented in Refs. [1,2], $BR(B^+ \to K^+X(1835)$, $X(1835) \to \eta'\pi^+\pi^-) \sim 3 \times 10^{-6}$ is obtained. Based on Eqs. (19) $BR(B^+ \to K^+X(1835), X(1835) \to \rho\rho, K^*\bar{K}^*)$ are in the range of 10^{-6}. Detailed studies of these B decays are beyond the scope of this paper.

VII. QUARK COMPONENTS

The study presented in this paper shows that the possibility of $X(1835)$ as a 0^{-+} glueball cannot be ruled out. The predictions made in this study are based on that $X(1835)$ is a pure glueball. On the other hand, because of the interactions between gluons and quarks it is natural that $X(1835)$ contains quark components. A 0^{-+} glueball with lower mass is obtained from QCD sum rule [18]. However, quenched lattice predicts the mass at about 2.5 GeV. A large downward shift to about 1835 MeV would imply a substantial quark-antiquark components in $X(1835)$. The quark components of $X(1835)$ can be estimated. Using the state of $X(1835)$

$$|X\rangle = \mathrm{con}\theta|G\rangle + \sin\theta|q\bar{q}\rangle,$$
$$m_X^2 = \cos^2\theta m_G^2 + \sin^2\theta m_Q^2 + \sin\theta\cos\theta(\langle G|m^2|q\bar{q}\rangle + \langle q\bar{q}|m^2|G\rangle). \quad (37)$$

The nondiagonal matrix elements between G and $q\bar{q}$ are at $O(g_s^2)$ which is at order of $\frac{1}{N_C}$ in N_C expansion, while m_G^2 and $m_{q\bar{q}}^2 \sim 1$. At the leading order in N_C expansion

$$\sin^2\theta = \frac{m_G^2 - m_X^2}{m_G^2 - m_{q\bar{q}}^2}. \quad (38)$$

The quark state is flavor singlet $\frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$ whose mass is proportional to $m_u + m_d + m_s$, therefore, $m_{q\bar{q}}^2$ is much smaller. In order to estimate $\sin^2\theta$ it is assumed that the mass of the quark state is about the same as the mass of the flavor singlet in η'. Using the effective meson theory [7], the masses of pseudoscalar mesons have been calculated [32]. In The same way the mass of this flavor singlet quark state is obtained as

$$m_{q\bar{q}}^2 = -\frac{4}{f_\pi^2}\langle\bar{\psi}\psi\rangle\frac{2}{3}\{m_u + m_d + m_s\}, \quad (39)$$

where $\langle\bar{\psi}\psi\rangle$ is the quark condensation. Using the results of Ref. [32],

$$m_{q\bar{q}}^2 = \frac{1}{3}(2m_K^2 + m_\pi^2) \quad (40)$$

is obtained. From quenched lattice [18] $m_G = 2.56 \pm 0.13$ GeV. Equation (38) determines $\sin\theta \sim 0.605 - 0.823$. As expected there is large $q\bar{q}$ components in $X(1835)$. Of course if the value of m_G determined by QCD sum rule [18] is taken, $\sin\theta$ is much smaller. If $X(1835)$ contains substantial $q\bar{q}$ components, it is very similar to η' $X(1835)$ should be observed in $J/\psi \to \omega(\phi) + X(1835)$. $X(1835)$ is a pseudoscalar and $BR(J/\psi \to \omega(\phi) + X(1835)) \propto k^3$, where k is the momentum of $X(1835)$

$$k^2 = \frac{1}{4m_J^2}(m_J^2 + m_X^2 - m_\omega^2)^2 - m_X^2.$$

Using the branching ratios of $BR(J/\psi \to \omega(\phi) + \eta')$, it is estimated $BR(J/\psi \to \omega(\phi) + X(1835)) \sim 10^{-5}$. On the other hand, if m_G takes the value determined by QCD sum rule very small quark components in $X(1835)$ and much smaller $BR(J/\psi \to \omega(\phi) + X(1835))$ should be expected.

The quark components of $X(1835)$ affect some of the predictions made in this paper. The predictions (19), (20), and (24)–(26) are taken as examples to study the effects of the quark components. In Ref. [7] the decays of a pseudoscalar meson to pairs of vector mesons have been calculated. In the same way the quark components of $X(1835)$ decays to VV can be computed. Equation (17) takes a new expression

$$\Gamma(X \to VV) = \frac{2f_V}{\pi}(g_{Xg}^2 \Delta G_V \cos\theta)^2 \times \left\{1 + \frac{N_C}{(4\pi)^2}\frac{1}{g^2}\frac{2m_X}{f_{q\bar{q}}}\frac{1}{g_{Xg}\Delta G_V}\tan\theta\right\}^2 \times \sqrt{q^2}\left(1 - \frac{4m_V^2}{q^2}\right)^{3/2}, \quad (41)$$

where $f_{q\bar{q}}$ is the unknown decay constant of the quark component of $X(1835)$. In the estimation of the mass of the quark component of $X(1835)$ it is taken to be f_π. There are unknown parameters in $\frac{N_C}{(4\pi)^2}\frac{1}{g^2}\frac{2m_X}{f_{q\bar{q}}}\frac{1}{g_{Xg}\Delta G_V}\tan\theta$ of Eq. (41). Taking $\sin\theta$ determined by quenched lattice, $\Delta G_V \sim 0.5$ and $f_{q\bar{q}} \sim f_\pi$, this factor is in the range of 0.72–2.56. The contribution of quark components is large. If QCD sum rule is used the contribution is small. The ratios (20), (25), and (26) are not affected by the quark components.

Finally, measurements of $J/\psi \to \omega(\phi) + X(1835))$ are very essential in determine the $q\bar{q}$ components of $X(1835)$.

VIII. SUMMARY

So far, the current data of $X(1835)$ can be understood by a 0^{-+} glueball. Predictions of testing the glueball nature of $X(1835)$ are made. Especially, the predicted ratios (20) and (26) should test the flavor independence of the decays of $X(1835)$. The cross sections of the productions of $X(1835)$ in two photon collisions depend on the gluon spin contents of vector mesons and the gluon spin content of a vector meson might not be small, therefore, larger cross sections are expected. On the other hand, if $X(1835)$ is a baryonium of $p\bar{p}$ it is natural that $BR(X \to p\bar{p})$ is large and $\eta'\pi\pi$ is a possible decay channel too. One of the main differences between a glueball and a $p\bar{p}$ baryonium is that a glueball is dominant by gluons and a $p\bar{p}$ baryonium state contains substantial u and d quark components. As pointed out that as a glueball the productions of $X(1835)$ in the hadronic decays of J/ψ are suppressed. Especially, the decays $J/\psi \to (\rho, \omega, \phi) + X(1835)$ are suppressed by $O(\alpha_s^2)$. However, if $X(1835)$ is a baryonium state there is no such suppression. $X(1835)$ as a $p\bar{p}$ baryonium state should be found in $J/\psi \to (\rho, \omega, \phi) + X(1835)$ decays. Also, as a $p\bar{p}$ baryonium state much smaller $BR(X(1835) \to K^*K^*, \gamma\phi)$ should be expected. Because of the same reason the decay channels such as $\rho\pi\pi$ (no $\rho\rho$), 4π (no $\rho\rho$) should have smaller branching ratios in the decays of a glueball $X(1835)$ and not small branching ratios in the decays of a baryonium $X(1835)$. Of course, a baryonium state will have many other predictions whose discussions are beyond the scope of this paper.

Finally, $J/\psi \to \omega(\phi) + X(1835)$ plays very important rule in determining the quark components of $X(1835)$.

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