X(1835): Natural candidate of η''s second radial excitation

Tao Huang[1,2] and Shi-Lin Zhu[3]

[1]*CCAST (World Laboratory) P.O. Box 8730, Beijing 100080, China*
[2]*Institute of High Energy Physics, Chinese Academy of Science, P.O. Box 918(4), Beijing 100049, China*
[3]*Department of Physics, Peking University, Beijing 100871, China*

(Received 15 November 2005; published 23 January 2006)

Recently BES collaboration observed one interesting resonance X(1835). We point out that its mass, total width, production rate, and decay pattern favor its assignment as the second radial excitation of η' meson very naturally.

DOI: 10.1103/PhysRevD.73.014023 PACS numbers: 12.39.Mk, 12.39.−x, 13.25.Jx

I. INTRODUCTION

A significant $p\bar{p}$ threshold enhancement was reported by BES Collaboration in the radiative decay $J/\psi \to \gamma p\bar{p}$ [1]. No similar signal was observed in the channel $\pi^0 p\bar{p}$. Assuming this enhancement arose from a resonance below threshold, the central value of the assumed resonance from S-wave fit was around 1859 MeV [1]. This year BES Collaboration observed a new resonance X(1835) in the $J/\psi \to \gamma\eta'\pi^+\pi^-$ channel with a statistical significance of 7.7σ [2]. The η' meson was detected in both $\eta\pi\pi$ and $\gamma\rho$ channels. There are roughly 264 ± 54 events. Its mass is $m_X = (1833.7 \pm 6.2 \pm 2.7)$ MeV, and its width is $\Gamma(X(1835)) = (67.7 \pm 20.3 \pm 7.7)$ MeV [2].

There are many speculations of the underlying structure of the $p\bar{p}$ threshold enhancement and X(1835) in literature. Proposed theoretical schemes include the t-channel pion exchange, some kind of threshold kinematical effects, a new resonance below threshold, even a $p\bar{p}$ bound state etc. [3–20].

The possibility of the $p\bar{p}$ threshold enhancement being a pseudoscalar glueball was discussed extensively in Ref. [21], and later in Refs. [22,23]. One serious obstacle of this assignment is its low mass. Lattice QCD predicts the pure scalar glueball around $1.5 \sim 1.7$ GeV [24]. Experimentally there exist overpopulation of scalar mesons around $1.3 \sim 1.7$ GeV. Pure pseudoscalar glueballs are predicted to lie around 2.6 GeV [24]. Therefore one needs to find a special powerful mixing mechanism to pull its mass from 2.6 GeV down to 1.835 GeV.

Under the strong assumption that the $p\bar{p}$ threshold enhancement and X(1835) are the same resonance, Zhu and Gao suggested X(1835) could be a $J^{PC}I^G = 0^{-+}0^+$ $p\bar{p}$ baryonium [19]. Such a scheme easily explains the large branching ratio of $X \to p\bar{p}$ observed by BES. Moreover, the dominant decay modes are $X(1835) \to \eta\pi\pi$ and $X(1835) \to \eta'\pi\pi$. Three-body decay modes with strangeness are suppressed due to the absence of explicit strangeness within a $p\bar{p}$ baryonium [4,19]. BES collaboration did observe X(1835) in the $\eta'\pi\pi$ channel. However they have not reported any positive information on the $\eta\pi\pi$ mode. The latter mode should have bigger branching ratio if X(1835) is a $p\bar{p}$ baryonium [19]. If future experimental search fails to observe X(1835) in the $\eta\pi\pi$ final states, one may challenge either the baryonium assignment or the initial assumption.

In retrospect, there is no strong experimental evidence that the $p\bar{p}$ threshold enhancement and X(1835) are the same resonance. Very probably they have completely different underlying structures. In fact we find that X(1835) has a natural interpretation as η''s second radial excitation. In this short note, we shall discuss its mass, total width, production rate, and decay pattern to convince readers of this assignment.

II. MASS, DECAY WIDTH, AND PRODUCTION RATE

There are nine low-lying pseudoscalar mesons π, K, η, η'. The mass splitting between η and η' is mainly caused by the axial anomaly. In the large N_c limit, the contribution from the anomaly vanishes [25]. Then these nine states would form a good nonet in the limit of exact SU(3) flavor symmetry.

For the radial excitations of π, K, η, η', the dominant part of their masses comes from nonperturbative QCD interaction, which is universal for them and much bigger than their mass splitting caused by different current quark mass. With nodes in their radial wave functions, one naively expects the axial anomaly will not affect the mass of η''s radial excitations significantly. In other words, the radial excitations of π, K, η, η' mesons tend to form a good nonet. In fact, all members of their first radial excitations are known to lie close to each other from PDG [26]. Their masses are $\pi(1300 \pm 100)$, $K(1460)$, $\eta(1295)$, $\eta'(1475)$. There may exist nearly ideal mixing between the two bare isoscalar states. Such a mixing enhances the $s\bar{s}$ component in $\eta'(1475)$ and causes the proximity of the masses of $\pi(1300)$ and $\eta(1295)$ [26]. Without mixing, $\eta'(1475)$ would easily decay into $\eta'\pi\pi$ final states. After mixing, $\eta'(1475)$'s wave function contains a large component of $s\bar{s}$. So its dominant decay modes are $K\bar{K}\pi$.

For the second radial excitations, we have $\pi(1800)$, $K(1830)$, $\eta(1760)$ [26]. Only η''s second radial excitation is missing. If this missing state is observed around 1835 MeV, it will not be a surprise. We suggest the recently observed resonance X(1835) as η''s second radial excitation. X(1835) can easily decay into $\eta'\pi\pi$ as η''s radial excitation while the mode $\eta\pi\pi$ is disfavored. From PDG, $\Gamma(\eta(1295)) = (55 \pm 5)$ MeV, $\Gamma(\eta'(1475)) = (50 \sim 90)$ MeV, $\Gamma(\eta(1760)) = (60 \pm 16)$ MeV. If X(1835) is η''s second radial excitation, the measured width $\Gamma(X(1835)) = (67.7 \pm 20.3 \pm 7.7)$ MeV is also very natural.

J/ψ decays into $\gamma\eta'$ more easily than into $\gamma\eta$ because intermediate virtual gluons are flavor-neutral and η' meson is mainly a SU(3) flavor singlet. From PDG [26], the branching ratio $B(J/\psi \to \gamma\eta') = (4.31 \pm 0.3) \times 10^{-3}$. Through η_1 and η_8 mixing, the branching ratio $B(J/\psi \to \gamma\eta) = (8.6 \pm 0.8) \times 10^{-4}$, which is a factor of 5 smaller. The radiative decay $J/\psi \to \gamma\eta(1295)$ has not been reported yet. The branching ratio of $B(J/\psi \to \gamma(\eta(1405) + \eta'(1475))) = (4.8 \pm 0.8) \times 10^{-3}$, which is very large. According to PDG, $\eta(1405)$ and $\eta'(1475)$ are two different states. We simply take $B(J/\psi \to \gamma\eta'(1475)) = (2.4 \pm 0.8) \times 10^{-3}$. It is interesting to note that the radiative decay of J/ψ into η''s first radial excitation is not suppressed severely. Therefore, there is no reason to expect strong suppression of the decay $J/\psi \to \gamma\eta'(1835)$.

Naively we assume a suppression factor of 3 compared with $J/\psi \to \gamma\eta'(1475)$ and arrive at

$$B(J/\psi \to \gamma\eta'(1835)) \sim 0.8 \times 10^{-3}. \quad (1)$$

Experimentally BES measured the product branching fraction [2]:

$$B(J/\psi \to \gamma\eta'(1835))B(\eta'(1835) \to \pi^+\pi^-\eta') = (2.2 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-4}. \quad (2)$$

If we further assume $B(\eta'(1835) \to \pi^+\pi^-\eta') \sim 40\%$, we have

$$B(J/\psi \to \gamma\eta'(1835)) \sim 0.6 \times 10^{-3}, \quad (3)$$

which is quite consistent with our naive expectation. Through the mixing of η_8's and η_1's bare second radial excitations, J/ψ can also decay into $\gamma\eta(1760)$. Similar to the $J/\psi \to \gamma\eta$ case, we assume its branching ratio of $J/\psi \to \gamma\eta(1760)$ is suppressed by a factor five compared to $J/\psi \to \gamma\eta'(1835)$, which is $\sim 1.2 \times 10^{-4}$. Experimentally this branching ratio is measured to be

$$B(J/\psi \to \gamma\eta(1760)) = (1.3 \pm 0.9) \times 10^{-4}. \quad (4)$$

In other words, the radiative branching ratio of $X(1835)$ is consistent with its assignment as η''s second radial excitation.

III. EFFECTIVE LAGRANGIAN FOR $X(1835) \to \eta'\pi\pi$ DECAY MODE

In this section we discuss S-wave decay mode $X(1835) \to \eta'\pi\pi$. Based on SU(3) flavor symmetry, we can construct a general effective Lagrangian.

$$\begin{aligned}\mathcal{L} &= g_1 \mathrm{Tr}(PM)\mathrm{Tr}(M^2) + g_2 \mathrm{Tr}(PM^2)\mathrm{Tr}(M) \\ &+ g_3 \mathrm{Tr}(PM^3) + g_4 \mathrm{Tr}(P)\mathrm{Tr}(M^3) \\ &+ g_5 \mathrm{Tr}(P)\mathrm{Tr}(M^2)\mathrm{Tr}(M) \\ &+ g_6 \mathrm{Tr}(P)\mathrm{Tr}(M)\mathrm{Tr}(M)\mathrm{T\,r}(M) \\ &+ g_7 \mathrm{Tr}(PM)\mathrm{Tr}(M)\mathrm{Tr}(M)\end{aligned} \quad (5)$$

where the matrix M is the ground state pseudoscalar nonet and P is its radial excitation:

$$M = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 + \frac{\eta_1}{\sqrt{3}} \end{pmatrix}, \quad (6)$$

$$P = \begin{pmatrix} \frac{\pi^0(1800)}{\sqrt{2}} + \frac{\eta(1760)}{\sqrt{6}} + \frac{\eta'(1835)}{\sqrt{3}} & \pi^+(1800) & K^+(1830) \\ \pi^-(1800) & -\frac{\pi^0(1800)}{\sqrt{2}} + \frac{\eta(1760)}{\sqrt{6}} + \frac{\eta'(1835)}{\sqrt{3}} & K^0(1830) \\ K^-(1830) & \bar{K}^0(1830) & -\frac{2}{\sqrt{6}}\eta(1760) + \frac{\eta'(1835)}{\sqrt{3}} \end{pmatrix}. \quad (7)$$

We have explicitly assumed X(1835) is η''s second radial excitation in Eq. (7). In Eq. (6), $\eta_{1,8}$ denotes SU(3) flavor octet and singlet member.

The g_6 and g_7 pieces in Eq. (5) involve two or three η_1 mesons. Hence these modes are kinematically forbidden. The pieces with g_4 and g_5 describe $\eta'(1835)$'s decay only. With these terms only, the octet members of the second radial excitations would not decay, in contradiction with available experimental data. Hence their contribution should be small. The g_2 term requires the decay final states of every member within the $\eta'(1835)$ nonet contain the SU(3) flavor singlet η_1, which is certainly not the case according to PDG [26]. Therefore, this term should not play a dominant role. Now we are left with only two pieces.

If we keep the g_3 term only, we have

$$\mathcal{L}_{g_3} = \frac{g_3}{6}\eta'(1835)\cdot\{(6\eta_1 + 3\sqrt{2}\eta_8)\cdot(\pi^0\pi^0 + 2\pi^+\pi^-) + 6\sqrt{3}(\bar{K}^0K^+\pi^- + K^0K^-\pi^+) + 3\sqrt{6}\pi^0(K^+K^- - K^0\bar{K}^0) + (12\eta_1 - 3\sqrt{2}\eta_8)(K^+K^- - K^0\bar{K}^0) + 2\eta_1^3 + 6\eta_1\eta_8^2 - \sqrt{2}\eta_8^3\} + \cdots \quad (8)$$

Naively one finds the coupling between $\eta'(1835)$ and $\eta_1\pi\pi$ is a factor of $\sqrt{2}$ larger than that between $\eta'(1835)$ and $\eta_8\pi\pi$. However the physical states are η, η', which is a mixture of η_1, η_8:

$$|\eta\rangle = \cos\theta|\eta_8\rangle - \sin\theta|\eta_1\rangle,$$
$$|\eta'\rangle = \sin\theta|\eta_8\rangle + \cos\theta|\eta_1\rangle \quad (9)$$

with the mixing angle $\theta \approx -\pi/9$ [26]. After inserting the above expressions into Eq. (8) we have

$$\mathcal{L}_{g_3} \sim \eta'(1835)\cdot\left(\frac{\pi^0\pi^0}{2} + \pi^+\pi^-\right)\cdot(0.7\eta' + 1.0\eta). \quad (10)$$

It is clear that (1) the decay width of $\eta'(1835) \to \eta'\pi^0\pi^0$ mode is half of $\eta'\pi^+\pi^-$ decay width. BES may be able to measure it; (2) the decay width of $\eta\pi\pi$ modes are a factor of 2 bigger than that of $\eta'\pi\pi$ modes even if we ignore the larger phase space; (3) the branching ratio of $\eta'(1835) \to \bar{K}^0K^+\pi^- + K^0K^-\pi^+$ is nearly the same as that of $\eta'\pi^+\pi^-$. BES's nonobservation of $\eta\pi\pi$ and $\bar{K}^0K^+\pi^- + K^0K^-\pi^+$ modes strongly indicate g_3 term does not play a dominant role when $\eta'(1835)$ decays.

With the above argument, we conclude the g_1 piece in Eq. (5) plays the dominant role when the $\eta'(1835)$ nonet decays into three pseudoscalar mesons via S-wave. After expanding this term we have

$$\mathcal{L}_{g_1} = (\eta'(1835)\eta_1 + \eta(1760)\eta_8)(2\pi^+\pi^- + \pi^0\pi^0 + 2K^+K^- + 2K^0\bar{K}^0 + \eta^2 + \eta'^2) + \cdots \quad (11)$$

From the above equation, the main decay modes of $\eta'(1835)$ is $\eta'\pi^+\pi^-$ and $\eta'\pi^0\pi^0$. $\eta'K^+K^-$ and $\eta'K^0\bar{K}^0$ modes are kinematically suppressed.

We would like to emphasize the decay mechanism from the g_1 piece is quite general for the decays of radial excitations. For example, $\psi(2S)$ and $\Upsilon(2S)$ decay into $J/\psi\pi\pi$ and $\Upsilon\pi\pi$ in the same way.

IV. DISCUSSION

In short summary, we have noticed that there does not exist strong experimental evidence that the $p\bar{p}$ threshold enhancement and X(1835) have the same underlying structure. Very probably they are two different states even if the enhancement arises from a subthreshold resonance. We point out that the mass, total decay width, production rate and decay pattern of X(1835) are consistent with its assignment as η''s second radial excitation. Its decay mode $X(1835) \to \eta'\pi^+\pi^-$ occurs through the emission of a pair of S-wave pions, which is quite general for the double-pion decays of ordinary radial excitations. $\eta'\pi^0\pi^0$ mode should be within reach of BES detectors. The confirmation of the absence of decay mode $X(1835) \to \eta\pi\pi$ in the future experimental search by BES collaboration will be a strong support of this classification. It is also very interesting for BES to (1) search X(1835) in the $\eta'4\pi$ modes; (2) look for the radiative decay $J/\psi \to \gamma\eta(1295)$; (3) search $\eta'(1475)$ in the $\eta'\pi\pi$ final states.

ACKNOWLEDGMENTS

T. H. was supported by the National Natural Science Foundation of China under Grant Nos. 10275070 and 10475084. S. L. Z. was supported by the National Natural Science Foundation of China under Grant Nos. 10375003 and 10421003, Ministry of Education of China, FANEDD, KJCX2-SW-N10, Key Grant Project of Chinese Ministry of Education (NO 305001) and SRF for ROCS, SEM.

[1] J. Z. Bai *et al.* (BES Collaboration), Phys. Rev. Lett. **91**, 022001 (2003).
[2] M. Ablikim *et al.*, (BES Collaboration), Phys. Rev. Lett. **95**, 262001 (2005).
[3] J. L. Rosner, Phys. Rev. D **68**, 014004 (2003).
[4] C.-S. Gao and S.-L. Zhu, Commun. Theor. Phys. **42**, 844 (2004).
[5] A. Datta and P. J. O'Donnell, Phys. Lett. B **567**, 273 (2003).
[6] B. S. Zou and H. C. Chiang, Phys. Rev. D **69**, 034004 (2004).
[7] B. Kerbikov, A. Stavinsky, and V. Fedotov, nucl-th/0310060.
[8] B. Kerbikov, A. Stavinsky, and V. Fedotov, Phys. Rev. C **69**, 055205 (2004).
[9] I. N. Mishustin, L. M. Satarov, T. J. Burvenich, H. Stoecker, and W. Greiner, Phys. Rev. C **71**, 035201 (2005).
[10] M. L. Yan, S. Li, B. Wu, and B. Q. Ma, Phys. Rev. D **72**, 034027 (2005).
[11] X. A. Liu, X. Q. Zeng, Y. B. Ding, X. Q. Li, H. Shen, and P. N. Shen, hep-ph/0406118.
[12] D. V. Bugg, Phys. Lett. B **598**, 8 (2004).

[13] X. G. He, X. Q. Li, and J. P. Ma, Phys. Rev. D **71**, 014031 (2005).

[14] C. H. Chang and H. R. Pang, Commun. Theor. Phys. **43**, 275 (2005).

[15] A. Sirbirtsev *et al.*, Phys. Rev. D **71**, 054010 (2005).

[16] B. Loiseau and S. Wycech, Int. J. Mod. Phys. A **20**, 1990 (2005).

[17] B. Loiseau and S. Wycech, Phys. Rev. C **72**, 011001 (2005).

[18] G. J. Ding and M. L. Yan, Phys. Rev. C **72**, 015208 (2005).

[19] S.-L. Zhu and C.-S. Gao, hep-ph/0507050.

[20] G. J. Ding, J. L. Ping, and M. L. Yan, hep-ph/0510013.

[21] N. Kochelev and D. P. Min, hep-ph/0508288; Phys. Rev. D **72**, 097502 (2005).

[22] X. G. He, X. Q. Li, X. Liu, and J. P. Ma, hep-ph/0509140.

[23] B. A. Li, hep-ph/0510093.

[24] C. Michael, hep-lat/0302001.

[25] J. F. Donoghue, E. Golowich, and B. R. Holstein, *Dynamics of Standard Model* (Cambridge University Press, Cambridge, England, 1992).

[26] S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004).