X(1835): A Possible Baryonium?

Shi-Lin Zhu$^{1,2}$ And Chong-Shou Gao$^1$

$^1$Department of Physics, Peking University, Beijing 100871, China
$^2$RCNP, Osaka University, Japan

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Abstract

We point out that (1) the large $par{p}$ coupling and suppressed mesonic coupling of X(1835) and (2) the suppression of the three-body strange final states strongly indicate that X(1835) may be a $par{p}$ baryonium. We also point out that the branching ratio of $X(1835) \rightarrow \eta\pi\pi$ should be bigger than that of $X(1835) \rightarrow \eta'\pi\pi$. If BES further confirms the non-observation of X(1835) in the $\eta\pi\pi$ channel, that will be very puzzling. Finally, X(1835) may be used a tetraquark generator if X(1835) is really established as a baryonium state.

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1 Introduction

BES Collaboration observed a significant threshold enhancement of $p\bar{p}$ mass spectrum in the radiative decay $J/\psi \rightarrow \gamma p\bar{p}$ [1]. No similar signal was observed in the channel $\pi^0 p\bar{p}$. Ignoring the final state interaction, the central value of this enhancement from S-wave fit was around 1859 MeV [1]. With the final state interaction in the isoscalar channel calculated in Ref. [2] as input, BES refit the mass and found it lies around 1830 MeV with a width $\Gamma = (0 \pm 93)$ MeV [3].

Theoretical work speculated many possibilities for the enhancement such as the t-channel pion exchange, some kind of threshold kinematical effects, a new resonance below threshold or even a $p\bar{p}$ bound state etc [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17].

In order to establish this enhancement as a new resonance X(1835), we argued that this state must be observed in the mesonic final states [18]. Based on the non-observation of X(1835) in the following final states $\pi^+\pi^-, 2\pi^0, K\bar{K}, 3\pi$ at that time [19], we concluded that the quantum number of this possible signal is very likely to be $J^{PC} = 0^{-+}, I^G = 0^+$ [18]. We called for the experimental search of X(1835) in the mesonic decay channels according to their priority: $\eta\pi\pi, \eta'\pi\pi, \eta\eta\eta, 4\pi, K\bar{K}\pi, \eta K\bar{K}, K\bar{K}\pi\pi, 6\pi$ [18].

Last month BES Collaboration reported preliminary results on X(1835) in the $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$ channel [3]. The $\eta'$ meson was detected in both $\eta\pi\pi$ and $\gamma\rho$ channels. There are roughly $264 \pm 54$ events. With a statistical significance of $7.7\sigma$, BES Collaboration measured the mass of X(1835) to be $(1833.7 \pm 6.2 \pm 2.7)$ MeV and its width to be $(67.7 \pm 20.3 \pm 7.7)$ MeV [3]. To the present authors, BES’s observation of X(1835) in the $\eta'\pi\pi$
is very encouraging while its non-observation of X(1835) in the \( \eta\pi\pi \) is a little confusing. In this short note, we shall try to explore the underlying structure of X(1860) using the available experimental information.

2 Expected typical properties of a baryonium

Because of its large \( p\bar{p} \) branching ratio and close proximity to \( p\bar{p} \) threshold, the possibility of X(1835) being a baryonium is particularly interesting. The study of nucleon and anti-nucleon bound states dated back to Fermi and Yang [20]. An extensive theoretical and experimental review can be found in Refs. [21, 22].

In the sector of nucleon-nucleon interaction, the short-range part was constrained and well determined using the properties of the light nuclei like deuteron and the available enormous nucleon-nucleon scattering data as inputs. In contrast, the nucleon anti-nucleon scattering data is scarce. The short-range part of \( N\bar{N} \) interaction \( V_{N\bar{N}} \) remains essentially unknown. Especially the annihilation contribution is very difficult to take into account. Because of very poor knowledge of the short range part of \( V_{N\bar{N}} \), some deeply-bound \( N\bar{N} \) states are always predicted using the phenomenological \( N\bar{N} \) potential. Experimentally none of them was found. A reliable calculation of the spectrum of \( N\bar{N} \) bound states is still too demanding at present.

In the following, we list some typical properties of X(1835) as a baryonium which one would naively expect.

2.1 Very large coupling of X(1835) with \( p\bar{p} \)

According to BES’s measurement, \( BR(J/\psi \rightarrow \gamma X) \cdot BR(X \rightarrow p\bar{p}) \sim 7 \times 10^{-5} \) [3]. Using \( BR(J/\psi \rightarrow \gamma X) \sim (0.5 - 2) \times 10^{-3} \) for a \( 0^+ \) meson, \( BR(X \rightarrow p\bar{p}) \sim (4 - 14)\% \) assuming \( \Gamma_X < 30 \text{ MeV} \) [1]. This branching ratio will increase if \( \Gamma_X \) increases [3]. Recall that \( 2m_p = 1876 \text{ MeV} \) while \( m_X = 1835 \text{ MeV} \) and \( \Gamma_X \approx 68 \text{ MeV} \). The decay of X(1835) into \( p\bar{p} \) occurs only from the tiny tail of its mass distribution. We may write an effective Lagrangian for this process:

\[
\mathcal{L} = g_{Xpp} \bar{p}i\gamma_5 pX + \text{H.c.} \tag{1}
\]

Then the decay width reads

\[
\Gamma(X \rightarrow p\bar{p}) = \frac{1}{8\pi}|g_{Xpp}|^2 \int_{4m_p^2}^{(M_X+\Gamma_X)^2} ds \sqrt{s-4m_p^2} f(s, M_X, \Gamma_X) \tag{2}
\]

where

\[
f(s, M_X, \Gamma_X) = \frac{M_X \Gamma_X}{\pi(s-M_X^2)^2+M_X^2 \Gamma_X^2} \tag{3}
\]

is the Breit-Wigner distribution. Note we have taken the upper limit of the integral to be \( (M_X + \Gamma_X)^2 \) instead of infinity. The reason is simple. The Breit-Wigner distribution is valid only for very narrow resonances. For any realistic case, the narrow resonance distribution should die off very quickly at \( \sqrt{s} = M_X + \Gamma_X \). Numerically we have

\[
\Gamma(X \rightarrow p\bar{p}) = 0.57 \times |g_{Xpp}|^2 \text{MeV} \tag{4}
\]
Even with $BR(X \to pp) \sim 10\%$, we get $g_{Xpp} \approx 3.5$ or

$$\alpha_{Xpp} = \frac{g_{Xpp}^2}{4\pi} \approx 1.0$$  \hspace{1cm} (5)

Now let’s move on to the decay mode $X(1835) \to \eta'\pi^+\pi^-$. Its decay width can be estimated using the following formula:

$$\Gamma(X \to \eta'\pi^+\pi^-) \approx \alpha_{X\eta'\pi\pi} \frac{\bar{k}^{2L+1}}{M_X^{2L}}$$  \hspace{1cm} (6)

where $\bar{k} \approx 400$ MeV is the averaged decay momentum and $L$ is the decay angular momentum. The above decay occurs through S-wave. Hence $L=0$. Assuming $\Gamma(X \to \eta'\pi^+\pi^-) \approx 20$ MeV, we arrive at

$$\alpha_{X\eta'\pi\pi} \approx 0.05$$  \hspace{1cm} (7)

which is in strong contrast with Eq. (5).

The strong enhancement of $pp$ coupling and severe suppression of mesonic coupling indicates that there may exist a large $pp$ component in the wave function of $X(1860)$. Invoking the baryonium hypothesis, the coupling difference can be ascribed to the underlying structure of $X(1835)$ easily.

### 2.2 Suppression of strange three-body final states

As a $pp$ bound state, $X(1835)$ contains three up and down quark anti-quark pairs. $X(1835)$ can fall apart into three pairs of non-strange mesons through color recombination. Since there is no valence strange quark within the proton, the three-body decays $X(1835) \to K\bar{K}\pi$ etc are suppressed by OZI rule. This simple conclusion is consistent with BES’s non-observation of $X(1835)$ in the $K\bar{K}\pi$ channel and observation in the $\pi^+\pi^-\eta'$. However, the four or five-body strange decay channels are not suppressed compared with those non-strange four/five body channels.

### 3 Puzzling decay pattern

In the chiral limit $m_q \to 0$, there are eight massless Goldstone bosons in QCD. Because of the axial anomaly, the $SU(3)$ flavor singlet pseudoscalar meson $\eta_1$ obtains finite mass even in the chiral limit. In fact, the majority of the $\eta_1$ mass comes from the anomaly. However, if we further take the large $N_c$ limit $N_c \to \infty$, $\eta_1$ becomes massless [23]. Now we have a massless nonet $M$:

$$M = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^- & \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & \bar{K}^0 \\ K^- & \bar{K}^0 & \frac{2}{\sqrt{6}}\eta_8 + \frac{\eta_1}{\sqrt{3}} \end{pmatrix}.$$  \hspace{1cm} (8)

We may write down the effective $pp$ three pseudoscalar meson interaction Lagrangian.

$$\mathcal{L} = g_D\text{Tr} (\bar{B}\{M^3, B\}^+) + g_F\text{Tr} (\bar{B}[M^3, B]_-)$$  \hspace{1cm} (9)
where the matrix $B$ is the nucleon octet:

$$B = \begin{pmatrix}
\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \frac{\Sigma^+}{\sqrt{3}} + \frac{\Lambda}{\sqrt{6}} & p \\
-\frac{\Sigma^0}{\sqrt{2}} & -\frac{\Sigma^-}{\sqrt{3}} + \frac{\Lambda}{\sqrt{6}} & n \\
-\frac{\Xi^-}{\sqrt{6}} & -\frac{\Xi^0}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \Lambda \\
\end{pmatrix}.$$  

After extracting the $p\bar{p}$ term, we have

$$\mathcal{L} \sim X(1860) \cdot \left( \frac{\pi^0\pi^0}{2} + \pi^+\pi^- \right) \cdot \left( \eta_1 + \frac{\eta_8}{\sqrt{2}} \right) \tag{11}$$

where we have replaced $p\bar{p}$ by $X(1835)$. Naively one finds the coupling between $X(1835)$ and $\eta\pi\pi$ is a factor of $\sqrt{2}$ larger than that between $X(1835)$ and $\eta_8\pi\pi$. However the physical states are $\eta, \eta'$, which is a mixture of $\eta_1, \eta_8$:

$$|\eta\rangle = \cos \theta |\eta_8\rangle - \sin \theta |\eta_1\rangle ,$$

$$|\eta'\rangle = \sin \theta |\eta_8\rangle + \cos \theta |\eta_1\rangle \tag{12}$$

with the mixing angle $\theta \approx -\frac{\pi}{3}$ [24]. After inserting the above expressions into Eq. (11) we have

$$\mathcal{L} \sim X(1860) \cdot \left( \frac{\pi^0\pi^0}{2} + \pi^+\pi^- \right) \cdot (0.7\eta' + 1.0\eta_8) . \tag{13}$$

From the above equation, it’s clear that (1) the decay ratio of $X(1835) \to \eta'\pi^0\pi^0$ mode is only a factor of four smaller than $\eta'\pi^+\pi^-$ mode. BES may be able to measure it; (2) $\eta\pi\pi$ modes are a factor of two bigger than $\eta'\pi\pi$ modes even if we ignore the larger phase space. Therefore, BES’s non-observation of $\eta\pi\pi$ modes is really puzzling.

We can interpret the above results from a more intuitive and transparent point of view. Let’s decompose the quark content of $\eta, \eta'$ explicitly.

$$\eta \approx \frac{\cos \theta}{\sqrt{6}} (u\bar{u} + d\bar{d} - 2s\bar{s}) - \frac{\sin \theta}{\sqrt{3}} (u\bar{u} + d\bar{d} + s\bar{s}) = 0.58 (u\bar{u} + d\bar{d}) - 0.57 s\bar{s} ,$$

$$\eta' \approx \frac{\sin \theta}{\sqrt{6}} (u\bar{u} + d\bar{d} - 2s\bar{s}) + \frac{\cos \theta}{\sqrt{3}} (u\bar{u} + d\bar{d} + s\bar{s}) = 0.40 (u\bar{u} + d\bar{d}) + 0.82 s\bar{s} . \tag{14}$$

If $X(1835)$ is a $p\bar{p}$ bound state, it mainly couples to the $(u\bar{u} + d\bar{d})$ component. It’s straightforward to conclude X(1835) decays into $\eta\pi\pi$ more easily. This is in conflict with BES’s preliminary results.

One natural scapegoat to explain the inconsistency is the axial anomaly intrinsically associated with $\eta_1$ since there may exists lots of glue inside X(1835). Let’s take a closer look at the $J/\psi$ radiative decay which is generally believed to be glue-rich. From PDG the branching ratio of $J/\psi \to \gamma\eta'$ is large: $(4.31 \pm 0.30) \times 10^{-3}$ while $J/\psi \to \gamma\eta$ was not observed [24]. This is an expected result since $\eta$ meson is mainly an octet which does not couple to $GG$ after $J/\psi$ decays into $\gamma GG$. Let’s move on to the exactly same three pseudoscalar meson radiative decays associated with X(1835). The branching ratio of $J/\psi \to \gamma\eta\pi\pi$ is huge: $(6.1 \pm 1.0) \times 10^{-3}$ while the $J/\psi \to \gamma\eta'\pi\pi$ mode can not be found from the summary table of PDG [24]. This counter-example shows that the axial anomaly may not play a very significant role in the $J/\psi$ three-pseudoscalar-meson radiative decays or three-pseudoscalar-meson decays of X(1835). Then comes the decay pattern puzzle
of X(1835): which mechanism is responsible for the suppression of the X(1835) → ηππ mode and enhancement of X(1835) → η′ππ mode?

Finally, let’s make one comment. Even in the extreme case that this decay is completely dominated by the axial anomaly, the η8 term is absent in Eq. (11). The mixing can still induce X(1835) → ηππ decays. The branching ratio between ηππ and η′π+π− modes should be larger than tan²θ = 13%.

4 Discussion

From the available BES’s preliminary data, we point out that the effective coupling constant between X(1835) and p¯p αXp¯p is order unity while its mesonic coupling constant αXη′ππ is strongly suppressed. Moreover the three-body strange final states are suppressed. All these information points toward the possibility of X(1835) being a p¯p baryonium.

Based on symmetry consideration and comparison with previous data, we point out that the branching ratio of X(1835) → ηππ should be bigger than that of X(1835) → η′ππ. If BES further confirms the non-observation of X(1835) in the ηππ channel, that will be very puzzling.

Finally we want to point out that X(1835) can be used as a tetraquark generator if it is really established a baryonium. A baryonium can easily transform into a tetraquark after emitting a light meson. In fact, BES Collaboration may search the decay final states of X(1835) to find out whether there exists possible tetraquark signals in the η′π invariant mass spectrum.

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References

[1] J. Z. Bai et al, BES Collaboration, Phys. Rev. Lett. 91, 022001 (2003).
[2] A.Sirbirtsev et al., hep-ph/0411386.
[3] S. Jin for the BES Collaboration, Plenary talk at the International Conference on QCD and Hadronic Physics, June 16-20, 2005, Beijing, China; http://www.phy.pku.edu.cn/~qcd/transparency/16-plen/jin.ppt
[4] G. J. Ding and M. L. Yan, arXiv:hep-ph/0502127.
[5] B. Loiseau and S. Wycech, arXiv:hep-ph/0501112.
[6] B. Loiseau and S. Wycech, Int. J. Mod. Phys. A 20, 1990 (2005) [arXiv:hep-ph/0411218].

[7] C. H. Chang and H. R. Pang, Commun. Theor. Phys. 43, 275 (2005) [arXiv:hep-ph/0407188].

[8] X. G. He, X. Q. Li and J. P. Ma, Phys. Rev. D 71, 014031 (2005) [arXiv:hep-ph/0407083].

[9] D. V. Bugg, Phys. Lett. B 598, 8 (2004) [arXiv:hep-ph/0406293].

[10] X. a. Liu, X. Q. Zeng, Y. B. Ding, X. Q. Li, H. Shen and P. N. Shen, arXiv:hep-ph/0406118.

[11] M. L. Yan, S. Li, B. Wu and B. Q. Ma, arXiv:hep-ph/0405087.

[12] I. N. Mishustin, L. M. Satarov, T. J. Burvenich, H. Stoecker and W. Greiner, Phys. Rev. C 71, 035201 (2005) [arXiv:nucl-th/0404026].

[13] B. Kerbikov, A. Stavinsky and V. Fedotov, Phys. Rev. C 69, 055205 (2004) [arXiv:hep-ph/0402504].

[14] B. Kerbikov, A. Stavinsky and V. Fedotov, arXiv:nucl-th/030060.

[15] B. S. Zou and H. C. Chiang, Phys. Rev. D 69, 034004 (2004) [arXiv:hep-ph/0309273].

[16] A. Datta and P. J. O’Donnell, Phys. Lett. B 567, 273 (2003) [arXiv:hep-ph/0306097].

[17] J. L. Rosner, Phys. Rev. D 68, 014004 (2003) [arXiv:hep-ph/0303079].

[18] C.-S. Gao, Shi-Lin Zhu, Commu. Theo. Phys. 42, 844 (2004).

[19] X.-Y. Shen for the BES Collaboration, Talk at the CLEOc/BES Joint Symposium, Jan, 2004, Beijing; Private communications with members of BES Collaboration.

[20] E. Fermi and C. N. Yang, Phys. Rev. 76, 1739 (1949).

[21] J.-M. Richard, Nucl. Phys. B (Proc. Suppl.) 86, 361 (2000).

[22] E. Klempt, F. Bradamante, A. Martin, and J.-M. Richard, Phys. Rep. 368, 119 (2002) and references herein.

[23] J. F. Donoghue, E. Golowich, B. R. Holstein, Dynamics of Standard Model, Cambridge University Press, 1992.

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