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X(1835) as Proton-Antiproton Bound State in Skyrme Model*

YAN Mu-Lin1)

(Interdisciplinary Center for Theoretical Study, Department of Modern Physics,
University of Science and Technology of China, Hefei 230026, China)

Abstract We present a review of the recent work related to interpreting the exotic particle X(1835) reported by BES as a $N\bar{N}$-baryonium in the Skyrme model. There are two evidences that support this interpretation: 1) There exists a classical $N\bar{N}$-Skyrmion solution with about $\sim$10MeV binding energy in the model; 2) The decay of this Skymion-baryonium is caused by annihilation of p-$\bar{\rm p}$ inside X(1835) through the quantum tunneling effect, and hence the most favorable decay channels are $\rm X\rightarrow\eta 4\pi$ or $\rm X\rightarrow\eta' 2\pi$. These lead to reasonable interpreting the data of BES, and especially to useful prediction on the decay mode of X(1835) for the experiment.

Key words exotic particle, proton-antiproton bound state, Skyrme model, p-$\bar{\rm p}$-annihilation, X(1835)-decay

1 Introduction

By using a sample of $5.8\times10^7 \rm J/\psi$ events collected with the BESⅡ detector, BES collaboration studied $\rm J/\psi\rightarrow\gamma p\bar{p}$ in 2003, and found out an anomalous enhancement near the mass threshold in the $\rm p\bar{p}$ invariant-mass spectrum from this decay process[1]. This enhancement was fitted with a subthreshold S-wave Breit-Wigner (BW) resonance function with a mass $M=1859^{+3+5}_{-10-25}\rm MeV/c^2$, a width $\Gamma<30\rm MeV/c^2$ (at the 90% C.L.), and a product branching fraction (BF) $B(\rm J/\psi\rightarrow\gamma X)\cdot B(X\rightarrow p\bar{p})=[7.0\pm0.4(stat)^{+1.9}_{-0.8}(syst)]\times10^{-5}$. These observations could be naively interpreted as signals for baryonium $\rm p\bar{p}$ bound state[2—7], and will be denoted as X(1835) hereafter. The BES-datum fit in Ref. [1] represents the simplest interpretation of the experimental results as indication of a baryonium resonance. As an unstable particle, the decays of X(1835) must be caused by the proton-antiproton annihilation inside the bound state X(1835)[4, 5]. This should be regarded as a significant feature for distinguishing X(1835)'s baryonium interpretation from other ones, say glueball, hybrid, or η''s excitation, etc. In Ref. [4], the $\rm p\bar{p}$-system has been studied by means of the Skyrme model. And an attractive potential at middle distance scale range between p and $\bar{\rm p}$, and a repulsive force at short distance of p-$\bar{\rm p}$ has been revealed. This means X(1835) can indeed be understood as a baryonium in the Skyrmion framework. Thus, to discuss the p-$\bar{\rm p}$ annihilations inside X(1835) in Skyrme model is legitimate. In Ref. [5], this issue has been investigated in detail by using coherent state method in the model following the Amado-Cannata-Dedoder-Locher-Lu's studies of the annihilations of p-$\bar{\rm p}$ scattering[8,10]. In this way, we found that $B(\rm X\rightarrow\eta4\pi)\gg B(X\rightarrow\eta2\pi)$, and then we argue $B(\rm X\rightarrow\eta'2\pi)$ (with $\eta'\rightarrow\eta2\pi$) must be much bigger than $B(\rm X\rightarrow\eta2\pi)$. This unusual prediction provides a criteria to identify whether X(1835) is a baryonium or not. Furthermore, to search the resonance of $\eta4\pi$ or $\eta'2\pi$ itself at the final state invariant mass 1800$\sim$1900MeV may reveal a full resonance peak for X-particle. Obviously, it is very significant to show

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1) E-mail: mlyan@ustc.edu.cn

the resonance via X-particle's mesonic decays both because the enhancement near the mass threshold in the $p\bar{p}$ invariant-mass spectrum from $J/\psi \to \gamma p\bar{p}$ decays has only shown a tail effect of the resonance and because a narrow resonance of $X \to \eta 2\pi$ has never been seen. Actually, the factor that there is no clear signal of narrow resonance of $\eta 2\pi$ at 1800 ~ 1900MeV corresponding to X-particle being seen in BES II was a serious obstacle to understanding the existence of X-particle at one time, because the quantum number assessment in Refs. [3, 7] means $X \to \eta\pi\pi$ should be the simplest decay mode for X-particle with the largest phase space. In this case, then, according to the analysis of Ref. [5], to search the mesonic resonance of $\eta 4\pi$ or $\eta' 2\pi$ with ($\eta' \to \eta 2\pi$) was urged. Consequently, by searching these decay processes, this obstacle was finely gotten over by a very beautiful experiment of BES II [11]. The full resonance peak of X(1835) has been revealed in the $J/\psi \to \gamma\eta'\pi^+\pi^-$ channel with a statistical significance of 7.7σ[11] (see Fig. 1). 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[11]. The mass and width of the X(1835) are not compatible with any known meson resonance[12]. In addition, the S-wave BW fit to the $p\bar{p}$ invariant-mass spectrum of Ref. [1] was improved in Ref. [11] by further considering the final state interaction effects in $X \to p\bar{p}$[13, 14]. The redoing corrected the original results ($M \sim 1859\text{MeV}/c^2$ with $\Gamma < 30\text{MeV}/c^2$) to be $M = 1831 \pm 7\text{MeV}/c^2$ with $\Gamma < 153\text{MeV}/c^2$ (at the 90% C.L.), which is consistent with the ones observed in Ref. [11] from $X \to \eta'\pi\pi$. This is a strong evidence which supports that the $p\bar{p}$-enhancement reported in Ref. [1] and the resonance of $\eta'\pi\pi$ reported by Ref. [11] are due to one and the same baryonium particle with $I^G(J^{PC}) = 0^+(0^{-+})$. Moreover, it has been revealed also that the relative $p\bar{p}$ decay strength is quite strong: $B(X\to p\bar{p})/B(X\to \pi^+\pi^-\eta') \sim 1/3$. All of these support that X-particle is a baryonium. In this talk I try to review the work in Refs. [4,5], in which X(1835) has been studied as proton-antiproton bound state in Skyrme model.

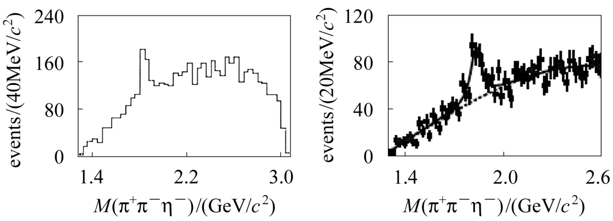

Fig. 1. The $\pi^+\pi^-\eta'$ invariant-mass distribution for selected event from both the $J/\psi \to \gamma\pi^+\pi^-\eta'(\eta' \to \eta\pi^+\pi^-)$ and $J/\psi \to \gamma\pi^+\pi^-\eta'$ ($\eta' \to \gamma\rho$) analysis. The bottom panel shows the fit (solid curve) to the data (points with error bars); the dashed curve indicates the background function. (see Ref. [11])

2 Nucleon-antinucleon bound state in Skyrme model

Skyrme's old idea[15] that baryons are chiral solitons has been successful in describing the static nucleon properties[16] since Witten's illustration that the soliton picture of baryons is consistent with QCD in the large N_c approximation[17]. Actually, it is a part of the large N_c-QCD theory. The Skyrme model has been widely used to discuss baryons and baryonic-system properties. Deuteron is a typical nucleon-nucleon system with baryon number 2, i.e., winding number 2, which has been extensively studied in this model. Generally, there are two Skyrmion ansatzes being used to explore this neutron-proton bound state in the Skyrme model: the product ansatz proposed by A. Jackson, A.D. Jackson and V. Pasquier[18], and the instanton ansatz proposed by M.F. Atiyah and N.S. Manton[19] for this non-trivial Skyrmion configurations. However, for the deuteron-like system $p\bar{p}$, the winding number (i.e., the baryon number in the Skyrme model) is zero, therefore the topology of the corresponding Skyrmion configurations is trivial, and only the product ansatz works. In the following, we employ the ungroomed product ansatz to investigate the $p\bar{p}$-system.

The Lagrangian for the $SU(2)$ Skyrme model is

$$\mathscr{L} = \frac{1}{16}F_\pi^2 \mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) + \frac{1}{32e^2}\mathrm{Tr}([(\partial_\mu U)U^\dagger, (\partial_\nu U)U^\dagger]^2) + \frac{1}{8}m_\pi^2 F_\pi^2 \mathrm{Tr}(U-1), \tag{1}$$

where $U(t,\boldsymbol{x})$ is the $SU(2)$ chiral field, expressed in terms of the pion fields:

$$U(t,\boldsymbol{x})=\sigma(t,\boldsymbol{x})+\mathrm{i}\pi(t,\boldsymbol{x})\cdot\tau. \tag{2}$$

We fix the parameters F_π and e as in Ref. [16], and our units are related to conventional units via

$$\frac{F_\pi}{4e}=5.58\mathrm{MeV},\quad \frac{2}{eF_\pi}=0.755\mathrm{fm}. \tag{3}$$

By using the hedgehog ansatz

$$U_\mathrm{H}(\boldsymbol{r})=\exp[\mathrm{i}\tau\cdot\hat{r}f(r)], \tag{4}$$

the ungroomed product ansatz describing the behavior of skyrmion and anti-skyrmion system without relatively rotation in the iso-space is of the form

$$U_\mathrm{s}=U_\mathrm{H}\left(\boldsymbol{r}+\frac{\rho}{2}\hat{z}\right)U_\mathrm{H}^\dagger\left(\boldsymbol{r}-\frac{\rho}{2}\hat{z}\right). \tag{5}$$

The skyrmion and the anti-skyrmion are separated along the $\hat{z}$-axis by a distance ρ. We find that the static potential in the ungroomed $S\bar{S}$ channel is physically more interesting, which satiates

$$U\rightarrow 1 \quad \text{when} \quad \rho\rightarrow 0. \tag{6}$$

Fixing our ansatz as above, we can get the static energy from the skyrmion Lagrangian:

$$M(\rho)=\int\mathrm{d}^3\boldsymbol{r}\left[-\frac{1}{2}\mathrm{Tr}(R_iR_i)-\frac{1}{16}\mathrm{Tr}([R_i,R_j]^2)\right], \tag{7}$$

where $i,j=1,2,3$. The right-currents R_μ are defined via

$$R_\mu=(\partial_\mu U)U^\dagger, \tag{8}$$

and we express the energy in the units defined above. In this picture, the binding energies for $S\bar{S}$ (which corresponds to the classical binding energies of $\mathrm{p\bar{p}}$) are

$$\Delta E_\mathrm{B}=2m_\mathrm{p}^c-M(\rho), \tag{9}$$

where $m_\mathrm{p}^c=867\mathrm{MeV}$ is the mass of a classical nucleon (or classical Skyrmion). A stable or quasi-stable $\mathrm{p\bar{p}}$-binding state corresponds to the Skyrmion configuration $U_\mathrm{s}(r,\rho_\mathrm{B})=U_\mathrm{H}\left(\boldsymbol{r}+\frac{\rho_\mathrm{B}}{2}\hat{z}\right)U_\mathrm{H}^\dagger\left(\boldsymbol{r}-\frac{\rho_\mathrm{B}}{2}\hat{z}\right)$ with $\Delta E_\mathrm{B}(\rho_\mathrm{B})<0$ and $\frac{\mathrm{d}}{\mathrm{d}\rho}(\Delta E_\mathrm{B}(\rho))|_{\rho=\rho_\mathrm{B}}=0$.

The numerical result of the static energy as a function of ρ is showed in Fig. 2. From it, we find that there is a quasi-stable $\mathrm{p\bar{p}}$-binding state:

$$\rho_\mathrm{B}\approx 2.5\mathrm{fm}, \tag{10}$$

$$\Delta E_\mathrm{B}(\rho_\mathrm{B})\approx 10\mathrm{MeV}. \tag{11}$$

Obviously, this is a deuteron-like molecule state with a rather small binding energy, and hence its mass is rather close to the threshold in proton-anti-proton mass spectrum. In this case, as long as one could further prove that this quasi-stable molecule state could have indeed a decay width, say $\sim 10\mathrm{MeV}$, then one could naturally conclude that this molecule resonance did respond for the near-threshold enhancement in ($\mathrm{p\bar{p}}$)-mass spectrum from $\mathrm{J}/\psi\rightarrow\gamma\mathrm{p\bar{p}}$ observed by BES, and this deuteron-like state should be the particle reported in experiment of Ref. [1]. We shall do so in the next section.

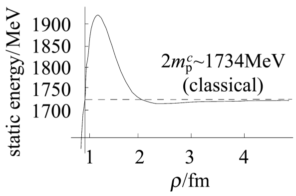

Fig. 2. The static energy of skyrmion-antiskyrmion system, where m_p^c is the classical single skyrmion mass without quantum correction.

Three remarks are in order:

1) To the $\mathrm{p\bar{p}}$-bound state, the absolute baryon number for separate (N-$\bar{\mathrm{N}}$) system is useful for understanding the inside structure of X-particle in the Skyrmion framework. By the Skyrme model, for (N-$\bar{\mathrm{N}}$)-system, $U(\boldsymbol{r},\rho)\equiv U_\mathrm{H}\left(\boldsymbol{r}+\frac{\rho}{2}\hat{z}\right)U_\mathrm{H}^\dagger\left(\boldsymbol{r}-\frac{\rho}{2}\hat{z}\right)$. The baryon density reads

$$\rho_\mathrm{B}(\boldsymbol{r},\rho)=\frac{\epsilon^{ijk}}{24\pi^2}\mathrm{Tr}[(U^\dagger(\boldsymbol{r},\rho)\partial_iU(\boldsymbol{r},\rho))\times (U^\dagger(\boldsymbol{r},\rho)\partial_jU(\boldsymbol{r},\rho))(U^\dagger(\boldsymbol{r},\rho)\partial_kU(\boldsymbol{r},\rho))], \tag{12}$$

and the total baryon number of the system with any separation ρ is zero, i.e.,

$$B(\rho)\equiv\int\mathrm{d}^3\boldsymbol{r}\rho_\mathrm{B}(\boldsymbol{r},\rho)=0. \tag{13}$$

But obviously the absolute baryon number for separate (N-$\bar{\mathrm{N}}$) is nonzero,

$$|B(\rho)|\equiv\int\mathrm{d}^3\boldsymbol{r}|\rho_\mathrm{B}(\boldsymbol{r},\rho)|\neq 0. \tag{14}$$

From the bottom panel of Fig. 3, one can see when N and $\bar{\rm N}$ are separated away largely, say $\rho > 1.5$fm, $|B(\rho)| \simeq 2$, and it is almost ρ-independent. When $\rho < 1.5$fm, $|B(\rho)|$ decreases sharply, and when $\rho < 0.5$fm the "baryonic matters" in the system are almost all annihilated away, i.e., $|B(\rho)| \rightarrow 0$. The curve of function $|B(\rho)|$ indicates that the configurations of N$\bar{\rm N}$-Skyrmion with $\rho_{\rm N\bar{N}} > 1.5$fm are molecular states of N-$\bar{\rm N}$, and when $\rho_{\rm N\bar{N}} < 0.5$fm, such configurations become mesonic states. The upper panel of Fig. 3 shows the curve of the static energy of Skyrmion-baryoniums (the same as Fig. 2). Obviously, since the distance between p and $\bar{\rm p}$ inside X $\rho_{\rm B} \approx 2.5$fm (see Eq. (10)) is much larger than ~ 1.5fm, and $|B(\rho_{\rm B})| \simeq 2$, we conclude that this baryonium configuration corresponding to the enhancement belongs to a molecular bound state composed of proton and antiproton.

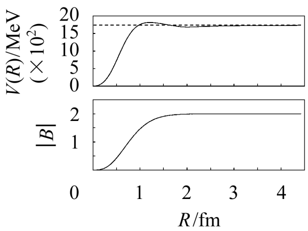

Fig. 3. The static energy of skyrmion-antiskyrmion system and the absolute value of baryon number of N$\overline{\rm N}$:1, The upper panel shows the curve of the static energy of skyrmion-antiskyrmion system (the same as Fig. 2); 2, The bottom panel shows the absolute value of baryon number of N$\overline{\rm N}$: $|B(\rho)|$.

2) The above discussion on the binding energies is somehow qualitative. Only the classical soliton energies of p$\bar{\rm p}$ have been taken into account there. Even though they should be the leading order of large $N_{\rm c}$ expansion, the semi-classical quantum correction to the p$\bar{\rm p}$ energies may decrease the small binding energies so as to vanish. Similar problem occurred in the discussions on deuteron by using τ_3-groomed product Skyrmion ansatz[18]. There were two methods to get over this difficulty for deuteron case: changing the ansatz[19], or improving the calculations of the classical soliton energies to include the contributions from the higher order of $N_{\rm c}$-expansion (or higher order of derivative expansion)[20]. The Skyrme model with 6-order derivative term has been explored in order to calculate the quark spin contents in proton[21, 22], and hence the model has been fixed. It should be interesting to pursue the semi-classical quantum corrections to the p$\bar{\rm p}$ in this generalized Skyme model. Namely, one could learn how to quantize the classical baryonium solutions without topology charge (see Eq. (13)) semi-classically.

3) Eq. (1) is the $SU(2)$-Skyrmion Lagrangian. It can be extended into $SU(3)$-one when $U(x)$ becomes 3×3-matrix function, the Wess-Zumino term is added, and the the $SU(2)$ chiral symmetry breaking term in (1) changes to $SU(3)$-one[23, 24]. The real world has three light flavors, and hence there are three flavor contents at least in the "sea" of $SU(2)$-nucleons[24]. The hyper-baryons with a strange quantum number, of course, only emerge in the $SU(3)$-Skyrmion theory. However, the fact that $SU(2)$-Skyrmion can rather rightly describe the properties of real nucleons indicates that the three flavor "sea" effects of nucleons have been partly (at least) covered by $SU(2)$-Skyrmion. The (p-$\bar{\rm p}$)-system discussed in this paper is flavor singlet and the baryon number free, and hence the qualitative discussions on it by means of $SU(2)$-Skyrmion should be consistent with one by $SU(3)$-Skyrmion.

3 A phenomenological model with a Skyrmion-type potential

In order to further catch the features of the Skyrmion prediction of p$\bar{\rm p}$ and to derive the decay width of this quasi-stable particle, we employ the potential model induced from the skyrmion picture of p$\bar{\rm p}$-interactions for the nucleons. For over fifty years there has been a general understanding of the nucleon-nucleon interaction as one in which there is, in potential model terms, a strong repulsive short distance core together with a longer range weaker attraction. The attractive potential at the middle range binds the neutron and the proton to form a deuteron. In comparison with the skyrmion result on the deuteron[25—28], we notice several remarkable features of the static energy $M(\rho)$ and the corresponding (p$\bar{\rm p}$)-potential $V(\rho)$. Firstly, the potential is attractive at $\rho > 2.0$fm, similar to the deuteron case. This is due to the reason that the interaction via pseudoscalar π-meson exchange is attractive for both quark-quark qq and quark-antiquark $q\bar{q}$ pairs. Physically, the attractive force between p and $\bar{p}$ should be stronger than that of pn. Therefore the fact that our result of the $p\bar{p}$-binding energy (see Eq. (11)) $\Delta E_B(\rho_B)(\approx 10\text{MeV})$ is larger than that of deuteron (2.225MeV) is quite reasonable physically. Secondly, there is a static Skyrmion energy peak at $\rho \sim 1$fm in Fig. 2. This means that the corresponding potential between p and $\bar{p}$ is repulsive at that range. This is an unusual and also an essential feature. The possible explanation for it is that the skyrmions are extended objects, and there would emerge a repulsive force to counteract the deformations of their configuration shapes when they are close to each other. Similar repulsive potential has also been found in previous numerical calculation. Thirdly, a well potential at middle ρ-range is formed due to the competition between the repulsive and attractive potentials mentioned above, similar to the deuteron case. But the depth should be deeper than that in the deuteron case, as argued in a QCD based discussion[3, 6]. The p and $\bar{p}$ will be bound to form a baryonium in this well potential. Finally, the potential turns to decrease quickly from ~ 2000MeV to zero when $\rho \to 0$. This means that there is a strong attractive force at $\rho \sim 0$. Physically, the skyrmions are destroyed at this ρ range, and $p\bar{p}$ are annihilated.

The qualitative features of the proton-neutron potential for the deuteron can be well described by a simple phenomenological model of a square well potential[29—31] with a depth which is sufficient to bind the pn $^3S_1$-state with a binding energy of -2.225MeV. Numerically, the potential width $a_{\rm pn}$ is about 2.0fm, and the depth is about $V_{\rm pn} = 36.5$MeV. Similarly, from the above illustrations on the features of the potential between p and $\bar{p}$ based on the Skyrmion picture, we now construct a phenomenological potential model for the $p\bar{p}$ system, as shown in Fig. 4, and it will be called as Skyrmion-type potential hereafter.

We take the width of the square well potential, denoted as $a_{p\bar{p}}$, as close to that of the deuteron, i.e., $a_{p\bar{p}} \sim a_{\rm pn} \simeq 2.0$fm. According to QCD inspired considerations[3, 6, 32—34], the well potential between q and $\bar{q}$ should be double (or more) attractive than the qq-case, i.e., the depth of the $p\bar{p}$ square well potential is $V_{p\bar{p}} \simeq 2V_{\rm pn} = 73$MeV. The width for the repulsive force revealed by the Skyrme model can be fitted by the decay width of the baryonium, and we take it to be $\lambda = 1/(2m_{\rm p}) \sim 0.1$fm, the Compton wave length of the bound state of $p\bar{p}$. The square barrier potential begins from $\rho \sim \lambda$, and the height of the potential barrier, which should be constrained by both the decay width and the binding energy of the baryonium, is taken as $2m_{\rm p} + h$, where $h \sim m_{\rm p}/4$. At $\rho \sim 0$, $V^{(p\bar{p})}(\rho) \sim -c\delta(\rho)$ with a constant $c > 0$.

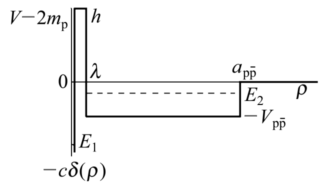

Fig. 4. The Skyrmion-type potential of $p\bar{p}$-system.

Analytically, the potential $V(\rho)$ is expressed as follows

$$V(\rho) = 2m_{\rm p} - c\delta(\rho) + V_c(\rho), \tag{15}$$

where

$$V_c(\rho) = \begin{cases} h = m_{\rm p}/4, & 0 < \rho < \lambda, \\ -V_{p\bar{p}} = -73\text{MeV}, & \lambda < \rho < a_{p\bar{p}}, \\ 0, & \rho > a_{p\bar{p}}. \end{cases} \tag{16}$$

With this potential, the Schrödinger equation for S-wave bound states is

$$\frac{-1}{2(m_{\rm p}/2)} \frac{\partial^2}{\partial \rho^2} u(\rho) + [V(\rho) - E]u(\rho) = 0, \tag{17}$$

where $u(\rho) = \rho\,\psi(\rho)$ is the radial wave function, $m_{\rm p}/2$ is the reduced mass. This equation can be solved analytically, and there are two bound states $u_1(\rho)$ and $u_2(\rho)$ (see Fig. 5 and Fig. 6): $u_1(\rho)$ with binding energy $E_1 < -V_{p\bar{p}} = -73$MeV is due to $-c\,\delta(\rho)$-function potential mainly, and $u_2(\rho)$ with binding energy $E_2 > -73$MeV is due to the attractive square well potential at middle range mainly. $u_1(\rho)$ is the vacuum state. And, clearly, $u_2(\rho)$ should correspond to a deuteron-like molecule state and it may be interpreted as the new $p\bar{p}$ resonance reported by BES[1]:

X(1835). It is also expected that corresponding binding energies $-E_2$ in the potential model provided in the above $\Delta E_B(\rho_B)$ (see Eq. (11)) are all in agreement with the data within errors of BES[1]. By fitting experimental data, we have

$$E_1 = -(2m_p - m_{\eta_0}) \simeq -976\text{MeV}, \quad (18)$$

$$E_2 = -17.2\text{MeV}. \quad (19)$$

Considering that its decay width will be derived soon (see Eq. (23)), we conclude that the near-threshold narrow enhancement in the $p\bar{p}$ invariant mass spectrum from $J/\psi \to \gamma p\bar{p}$ might be interpreted as a state of protonium in this potential model.

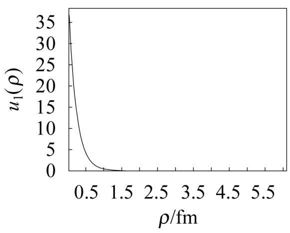

Fig. 5. The wave function $u_1(\rho)$.

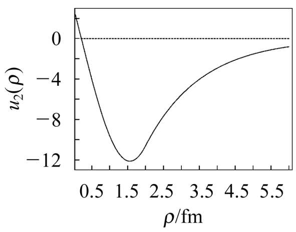

Fig. 6. The wave function $u_2(\rho)$.

In the skyrmion-type potential of $p\bar{p}$, there are two attractive potential wells: one is at $\rho \sim 0$ and the other is at middle scale, together with a potential barrier between them. At $\rho \sim 0$, the baryon- and anti-baryon annihilates. Naturally, we postulate that the bound states decay dominantly by annihilation and, therefore, we can derive the width of protonium state $u_2(\rho)$ by calculating the quantum tunnelling effect for $u_2(\rho)$ passing through the potential barrier. By WKB-approximation, the tunnelling coefficient (i.e., barrier penetrability) reads[31]

$$T_0 = \exp\left[-2\int_0^\lambda \mathrm{d}r\sqrt{m_p(h-E_2)}\right] = \exp\left[-2\lambda\sqrt{m_p(h-E_2)}\right]. \quad (20)$$

In the square well potential from λ to $a_{p\bar{p}}$, the time-period θ of round trip for the particle is

$$\theta = \frac{2[a_{p\bar{p}}-\lambda]}{v} = [a_{p\bar{p}}-\lambda]\sqrt{\frac{m_p}{V_{p\bar{p}}+E_2}}. \quad (21)$$

Thus, the state $u_2(r)$'s life-span is $\tau = \theta T_0^{-1}$, and hence the width of that state reads

$$\Gamma \equiv \frac{1}{\tau} = \frac{1}{a_{p\bar{p}}-\lambda}\sqrt{\frac{V_{p\bar{p}}+E_2}{m_p}} \exp\left[-2\lambda\sqrt{m_p(h-E_2)}\right]. \quad (22)$$

Numerically, substituting $E_2 = -17.2\text{MeV}$, $a_{p\bar{p}} = 2.0\text{fm}$ into (22), we obtain the prediction of Γ:

$$\Gamma \simeq 15.5\text{MeV}, \quad (23)$$

which is a reasonable number when comparing it with the experimental data[1]. This result indicates also that the $(p\bar{p})$-collision times per second in X are about

$$\nu = \Gamma/\hbar \simeq 2.35\times10^{22}\text{times/s}. \quad (24)$$

This reflects the possibility of $(p\bar{p})$-collisions inside X-particle in the sense of quantum theory. When that possibility $P = 1 = \nu\tau$, one reobtains the lifetime of X as $\tau = 1/\nu = 1/\Gamma$. Noting since the binding energy E_2 is rather small (comparing with $2m_p$), the annihilations which cause X(1835) to be unstable are almost at rest.

Two remarks are in order:

1) Because there are adjustable parameters (c, h, λ, $V_{p\bar{p}}$, $a_{p\bar{p}}$) in our potential model, it is no doubt to fit the renewed experimented data in Ref. [11].

2) The quantum numbers of X-particle corresponding to $u_2(\rho)$ are $I^G(J^{PC}) = 0^+(0^{-+})$[3, 7], and hence the particle corresponding to $u_1(\rho)$ must be of $I^G(J^{PC}) = 0^+(0^{-+})$ also. Considering the range for nonzero $u_1(\rho)$ is of $\rho \sim 0$ (see Fig. 5), and then $|B(\rho \sim 0)| \sim 0$ (see Fig. 3), the $u_1(\rho)$-particle must be a meson (a point-like particle) rather than a baryonim. Thus, the possible candidates are η or η'. Moreover, the gluon contents for $u_1(\rho)$-particle, $u_2(\rho)$-particle X(1835) and $(p\bar{p})$ should be the same. Thus, only η' is available, and then we conjectured in the above that the particle corresponding to $u_1(\rho)$ is η'.

4 Proton-antiproton annihilation inside X(1835) and its mesonic decays

In the above, we have pointed out that $N\bar{N}$-annihilation causes the $p\bar{p}$ baryonium X(1835) to be unstable. In order to find out what decay processes are of the most favorable channels, we now pursue the $N\bar{N}$ annihilations inside X(1835) in the Skyrme model. As a nucleon model inspired by QCD, the Skyrme model has a very useful advantage in describing $N\bar{N}$ annihilation: this effective theory provides a self-contained dynamics that encompasses nonlinear processes such as meson production, baryon excitation, and annihilation. The Skyrme model requires no additional dynamical assumption, such as the ad hoc dynamical behavior of the color-confinement wall that must be assumed in bag models. The studies of annihilation in the Skyrme model[35, 36] have suggested that annihilation proceeds very rapidly when the baryon and antibaryon collide and that the product of this rapid annihilation is a pion pulse or coherent pion wave. The annihilation of $N\bar{N}$ scattering process at rest has been investigated by Amado, Cannata, Dedoder, Locher, Shao and Lu (ACDLSL)[8—10] in the Skyme model by using the coherent state method. When the proton and antiproton collide, they will be annihilated into mesons rapidly. ($p\bar{p}$)-annihilation at rest but without considering the P- and G-parity has been investigated by using coherent state method in Refs. [8—10]. In the following, we introduce ACDLSL's coherent state of Refs. [8—10] briefly, and then, the studies in Ref. [5] which lead to revealing the most favorable channels for X-decays.

4.1 Coherent state for annihilation of $N\bar{N}$ scattering process at rest

1) Coherent state is the eigenstate of annihilation operator, $a|\lambda\rangle=\lambda|\lambda\rangle$:

$$|\lambda\rangle=\mathrm{e}^{-|\lambda|^2/2}\ \mathrm{e}^{\lambda a^\dagger}|0\rangle, \tag{25}$$

which is useful for the quantum optics, e.g., to describe the purse from rapid radiations of photons in laser[37]. To free quantum scalar field $\phi(x)=\phi^{(+)}(x)+\phi^{(-)}(x)=\int\frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^{3/2}\sqrt{2\omega_{\boldsymbol{k}}}}(a_{\boldsymbol{k}}\mathrm{e}^{-\mathrm{i}k\cdot x}+a^\dagger_{\boldsymbol{k}}\mathrm{e}^{\mathrm{i}k\cdot x})$, the normalized quantum state $|f\rangle$ defined by

$$|f\rangle=\exp\left[-\frac{1}{2}\int\mathrm{d}^3\boldsymbol{k}|f(\boldsymbol{k})|^2+\int\mathrm{d}^3\boldsymbol{k}f(\boldsymbol{k})a^\dagger_{\boldsymbol{k}}\right]|0\rangle, \tag{26}$$

which is the coherent state of $\phi(x)$, i.e.,

$$\phi^{(+)}(x)|f\rangle=\varphi(x)|f\rangle,\text{with}$$
$$\varphi(x)=\int\frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^{3/2}\sqrt{2\omega_{\boldsymbol{k}}}}\mathrm{e}^{-\mathrm{i}k\cdot x}f(\boldsymbol{k}). \tag{27}$$

2) The coherent state with fixed 4-momentum and isospin[8—10]: Fig. 3 shows when the distance between Skyrmion and anti-Skyrmion ρ less than $\sim$1fm, $|B(\rho)|$ will decrease sharply. This means the pions radiated from the annihilation of $N\bar{N}$ form a purse. The processes are very rapid, and are similar to the photon radiated from the laser. Considering this feature of $N\bar{N}$-annihilation, a coherent state description of the $N\bar{N}$ scattering annihilation has been suggested in Ref. [8], and a coherent state with fixed 4-momentum and isospin[8—10] has been formed by Amado, Cannata, Dedoder, Locher, Shao and Lu (ACDLSL) as follows

$$|K,I,I_z\rangle_{\mathrm{ACDLSL}}=\int\frac{\mathrm{d}^4x}{(2\pi)^4}\frac{\mathrm{d}\Omega_{\hat{\boldsymbol{n}}}}{\sqrt{4\pi}}\,\mathrm{e}^{\mathrm{i}K\cdot x}|f,x,\hat{\boldsymbol{n}},2\rangle Y^*_{I,I_z}(\hat{\boldsymbol{n}}), \tag{28}$$

where

$$|f,x,\hat{\boldsymbol{n}},2\rangle = [\mathrm{e}^{F(x,\hat{\boldsymbol{n}})}-F(x,\hat{\boldsymbol{n}})-1]|0\rangle, \tag{29}$$
$$F(x,\hat{\boldsymbol{n}}) = \int\mathrm{d}^3\boldsymbol{k}\mathrm{e}^{-\mathrm{i}k\cdot x}f(\boldsymbol{k})a^\dagger_{\boldsymbol{k}}\cdot\hat{\boldsymbol{n}},$$
$$|f(\boldsymbol{k})|^2 = \frac{C\boldsymbol{k}^2}{(\boldsymbol{k}^2+\alpha^2)^2(\omega^2_{\boldsymbol{k}}+\gamma^2)^2\omega^2_{\boldsymbol{k}}} \tag{30}$$

where $\alpha=\gamma=2m_\pi$. Then the π-radiations from $|K,I,I_z\rangle_{\mathrm{ACDLSL}}$ can be discussed by calculating the mean number of charged $\pi^\pm$ and π^0 ($\mu=\pm,0$):

$$\hat{\boldsymbol{N}}_\mu={}_{\mathrm{ACDLSL}}\langle K,I,I_z|\int\mathrm{d}^3ka^\dagger_{\boldsymbol{k},\mu}a_{\boldsymbol{k},\mu}|K,I,I_z\rangle_{\mathrm{ACDLSL}}.$$

The function $|f(\boldsymbol{k})|^2$ in Eq. (30) comes from the following considerations provided in Ref. [9]. The π-field equation is:

$$\left(\nabla^2-\frac{\partial^2}{\partial t^2}-\mu^2\right)\Phi(\boldsymbol{r},t)=S(\boldsymbol{r},t). \tag{31}$$

Here $S(\mathbf{r},t)$ is the source of the pion field Φ. Inspired by the Skyrmion calculations[35,36], a very simple spherically symmetric form of $S(\boldsymbol{r},t)$ has been suggested in Refs. [8,9] by Amado, Cannata, Dedonder, Locher and Shao (i.e., ACDLS-ansatz) as follows

$$S(\boldsymbol{r},t)=S(\boldsymbol{r},t)_{\rm ACDLS}=\begin{cases}0, & \text{if } t<0,\\ S_0\dfrac{{\rm e}^{-\alpha r}}{r}t{\rm e}^{-\gamma t}, & \text{if } t>0.\end{cases} \tag{32}$$

By using $f(\boldsymbol{k})=-{\rm i}\sqrt{2\pi}S(\boldsymbol{k},\omega_k)/(2\omega_k)$ and

$$S(\boldsymbol{k},\omega_k)=\int\frac{{\rm d}^3\boldsymbol{r}\,{\rm d}t}{(2\pi)^2}\exp(-{\rm i}\boldsymbol{k}\cdot\boldsymbol{r}+{\rm i}\omega_k t)S(\boldsymbol{r},t),$$

we get Eq. (30).

4.2 Coherent states with fixed *G*- and *P*-parities

We address that the coherent state $|K,I,I_z\rangle_{\rm ACDLSL}$ is G- and P-parities free, therefore it can't be used to discuss the X(1835)-decays. In Ref. [5], X(1835) has been treated as meson radiation source with $I^G(J^{PC})=0^+(0^{-+})$. The coherent state with fixed 4-momentum, isospin, G-parity(+) and P-parity(−) has been constructed in Ref. [5] as follows

$$|K,I,I_z\rangle_{GP}=\int\frac{{\rm d}^4x}{(2\pi)^4}\frac{{\rm d}\Omega_{\hat{\boldsymbol{n}}}}{\sqrt{4\pi}}\,{\rm e}^{{\rm i}K\cdot x}|f,g,x,\hat{\boldsymbol{n}},2\rangle Y^*_{I,I_z}(\hat{\boldsymbol{n}}), \tag{33}$$

where

$$\begin{aligned}|f,g,x,\hat{\boldsymbol{n}},2\rangle\ =\ &[{\rm e}^{F(x,\hat{\boldsymbol{n}})}+{\rm e}^{G(x,\hat{\boldsymbol{n}})}-F(x,\hat{\boldsymbol{n}})-\\&G(x,\hat{\boldsymbol{n}})-{\rm e}^{-F(x',\hat{\boldsymbol{n}})}-{\rm e}^{-G(x',\hat{\boldsymbol{n}})}-\\&F(x',\hat{\boldsymbol{n}})-G(x',\hat{\boldsymbol{n}})]|0\rangle,\end{aligned}$$

$$F(x,\hat{\boldsymbol{n}})=\int{\rm d}^3\boldsymbol{k}{\rm e}^{-{\rm i}k\cdot x}f(\boldsymbol{k})\boldsymbol{a}^\dagger_{\boldsymbol{k}}\cdot\hat{\boldsymbol{n}}+\int{\rm d}^3\boldsymbol{q}{\rm e}^{-{\rm i}q\cdot x}g(\boldsymbol{q})b^\dagger_{\boldsymbol{q}},$$

$$G(x,\hat{\boldsymbol{n}})\ =\ -\int{\rm d}^3\boldsymbol{k}f(\boldsymbol{k})\boldsymbol{a}^\dagger_{\boldsymbol{k}}\cdot\hat{\boldsymbol{n}}\ {\rm e}^{-{\rm i}k\cdot x}+\int{\rm d}^3\boldsymbol{q}{\rm e}^{-{\rm i}q\cdot x}g(\boldsymbol{q})b^\dagger_{\boldsymbol{q}},$$

$$|f(\boldsymbol{k})|^2\ =\ \frac{C\ \boldsymbol{k}^2}{(\boldsymbol{k}^2+\alpha^2)^2(\omega^2_{\boldsymbol{k}}+\gamma^2)^2\omega^2_{\boldsymbol{k}}}, \tag{34}$$

$$|g(\boldsymbol{k})|^2\ =\ |f(\boldsymbol{k})|^2|_{m_\pi\to m_\eta}, \tag{35}$$

where $\alpha=\gamma=2m_\pi$, and $x'=(-\boldsymbol{x},t)$. Because both π- and η-fields are pseudo-Goldstone bosons in QCD, the ACDLS-ansatz Eq. (32) has been used for both π-and η-particle radiations to determine $|f(\boldsymbol{k})|^2$ and $|g(\boldsymbol{k})|^2$ in Eqs. (34) and (35). C is the strength and can be fixed by requiring that the average energy is the energy released in annihilation, which is equal to $2m_{\rm p}$, i.e.,

$$2m_{\rm p}=\int{\rm d}^3\boldsymbol{k}\left(\sqrt{\boldsymbol{k}^2+m^2_\pi}|f(\boldsymbol{k})|^2+\sqrt{\boldsymbol{k}^2+m^2_\pi}|g(\boldsymbol{k})|^2\right), \tag{36}$$

where the strengthes of C in both $|f(\boldsymbol{k})|$ and $|g(\boldsymbol{k})|$ are the same because both π and η are pseudo-Goldstone bosons in QCD, and the influence on C due to light quark flavor symmetry breaking is ignored (noting the effects of the light quark flavor symmetry breaking to $|f(\boldsymbol{k})|$ and $|g(\boldsymbol{k})|$ are taken into account via $m_\pi\neq m_\eta$). The unitary operators $\hat{G}$, $\hat{P}$ can be expressed as follows

$$\hat{P}\ =\ \exp\left[{\rm i}\frac{\pi}{2}\sum_{j,\boldsymbol{k}}(a^+_{\boldsymbol{k},j}a_{-\boldsymbol{k},j}+b^+_{\boldsymbol{k}}b_{-\boldsymbol{k}}+a^+_{\boldsymbol{k},j}a_{\boldsymbol{k},j}+b^+_{\boldsymbol{k}}b_{\boldsymbol{k}})\right],$$

$$\begin{aligned}\hat{G}\ =\ &\exp\left[{\rm i}\frac{\pi}{2}\sum_{j,\boldsymbol{k}}(a^+_{\boldsymbol{k},-1}a_{\boldsymbol{k},1}+a^+_{\boldsymbol{k},1}a_{\boldsymbol{k},-1}-\right.\\&\left.a^+_{\boldsymbol{k},1}a_{\boldsymbol{k},1}-a^+_{\boldsymbol{k},-1}a_{\boldsymbol{k},-1})\right]\times\\&\exp\left[-\frac{\pi}{\sqrt{2}}\sum_{\boldsymbol{k}}(a^+_{\boldsymbol{k},0}a_{\boldsymbol{k},1}+a^+_{\boldsymbol{k},0}a_{\boldsymbol{k},-1}-\right.\\&\left.a^+_{\boldsymbol{k},1}a_{\boldsymbol{k},0}-a^+_{\boldsymbol{k},-1}a_{\boldsymbol{k},0})\right].\end{aligned}$$

It is easy to check the following equations

$$\begin{aligned}\hat{G}a^\dagger_{\boldsymbol{p},i}\hat{G}^\dagger\ &=\ -a^\dagger_{\boldsymbol{p},i}\ ,\\ \hat{G}b^\dagger_{\boldsymbol{q}}\hat{G}^\dagger\ &=\ b^\dagger_{\boldsymbol{q}}\ ,\\ \hat{P}a^\dagger_{\boldsymbol{p},i}\hat{P}^\dagger\ &=\ -a^\dagger_{-\boldsymbol{p},i}\ ,\\ \hat{P}b^\dagger_{\boldsymbol{q}}\hat{P}^\dagger\ &=\ -b^\dagger_{-\boldsymbol{q}}\ ,\end{aligned} \tag{37}$$

where $i=1,0,-1$ corresponding to π^+,π^0,π^-, and $b^\dagger_q$ represents the creation operator for a pseudo-scalar Goldstone particle with G-parity (+), P-parity (−) and isospin $I=0$. So, it is η.

4.3 π- and η-radiations from $|K,I,I_z\rangle_{GP}$

The probability of ($N_\pi\pi$, $N_\eta\eta$)-radiations from $|K,I,I_z\rangle_{GP}$ is:

$$\begin{aligned}P(N_\pi,N_\eta)\ =\ &\frac{1}{N_\pi!N_\eta!}\int\prod_{i=1}^{N_\pi}{\rm d}^3\boldsymbol{p}_i\prod_{j=1}^{N_\eta}{\rm d}^3\mathbf{q}_j\ \times\\&|\langle\boldsymbol{p}_1\boldsymbol{p}_2\cdots\boldsymbol{p}_{N_\pi}\boldsymbol{q}_1\boldsymbol{q}_2\cdots\boldsymbol{q}_{N_\eta}|K,I,I_z\rangle_{GP}|^2=\\&\frac{1}{\mathscr{I}(K)}\frac{16I(K,N_\pi,N_\eta)F(N_\pi,I)}{N_\pi!N_\eta!}.\end{aligned} \tag{38}$$

where $\mathscr{I}(K)$ is the normalization factor:

$$\mathscr{I}(K)=\sum_{m+n\geqslant 2;\, m \text{ is even},\, n \text{ is odd}} \frac{16I(K,m,n)}{m!n!}F(m,I)$$

where

$$I(K,m,n) = \int \delta^4(K-\sum_{i=1}^{m}p_i-\sum_{j=1}^{n}q_j)\prod_{i=1}^{m}\mathrm{d}^3\boldsymbol{p}_i|f(\boldsymbol{p}_i)|^2 \times \prod_{j=1}^{n}\mathrm{d}^3\boldsymbol{q}_j|g(\boldsymbol{q}_j)|^2$$

and

$$F(m,I)=\int\frac{\mathrm{d}\Omega_{\hat{\boldsymbol{n}}}\mathrm{d}\Omega_{\hat{\boldsymbol{n}}'}}{4\pi}Y^*_{II_z}(\hat{\boldsymbol{n}})Y_{II_z}(\hat{\boldsymbol{n}}')(\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{n}}'^*)^m = \begin{cases} 0 & I>m \text{ or } I-m \text{ is odd} \\ \dfrac{m!}{(m-I)!!(I+m+1)!!} & I\leqslant m \text{ and } I-m \text{ is even.}\end{cases}$$

Noting the branching fraction $B(\mathrm{X}(1835)\rightarrow m\pi+n\eta) \propto P(m,n)$, the ratios of $B(\mathrm{X}\rightarrow\eta 4\pi)/B(\mathrm{X}\rightarrow\eta 2\pi)$, etc can be calculated:

$$\frac{B(\mathrm{X}\rightarrow\eta 4\pi)}{B(\mathrm{X}\rightarrow\eta 2\pi)} = \frac{I(K,4,1)}{I(K,2,1)}\frac{7}{300}\simeq 1.8\times 10^4, \quad (39)$$

$$\frac{B(\mathrm{X}\rightarrow\eta 2\pi)}{B(\mathrm{X}\rightarrow 3\eta)} = \frac{I(K,2,1)}{I(K,0,3)}\frac{2}{3}\simeq 5.9. \quad (40)$$

These are desirous results. The process of $\mathrm{X}\rightarrow\eta 4\pi$ is a very favorable channel, and the branching fraction of the simplest decay channel $\mathrm{X}\rightarrow\eta 2\pi$ is suppressed by about 4 orders compared with one of $\mathrm{X}\rightarrow\eta 4\pi$.

4.4 An intuitive picture

1) Naively, the number of valence quarks in X(1835)(or $(\mathrm{p}\bar{\mathrm{p}})$) is equal to the number of valence quarks in $(\eta\pi\pi)$.

2) However, the gluon contents for $(\mathrm{p}\bar{\mathrm{p}})$ and $(\eta\pi\pi)$ are different. Skyrmion tells us that the gluon mass-percentage in proton (or antiproton) is larger than that for the π or η.

3) This indicates that there are some “redundant gluons” that are left over in the process of $\mathrm{X}\equiv(\mathrm{p}\bar{\mathrm{p}})\rightarrow\eta 2\pi$. Consequently, the process should be expressed as

$$\mathrm{X}\equiv(\mathrm{p}\bar{\mathrm{p}})\rightarrow\eta 2\pi\mathrm{G}.$$

where G represents the “redundant gluons”. Going further

$$\mathrm{X}\equiv(\mathrm{p}\bar{\mathrm{p}})\rightarrow\eta 2\pi\underset{\hookrightarrow\pi\pi}{\mathrm{G}}. \quad (41)$$

Therefore, the most favorable X-particle decay process should be $\mathrm{X}\rightarrow\eta 4\pi$, instead of $\mathrm{X}\rightarrow\eta 2\pi$. Most likely, G and η could combine to form the meson η', in which case Eq. (41) becomes

$$\mathrm{X}\rightarrow 2\pi(\eta\mathrm{G}) = 2\pi\ \underset{\hookrightarrow\eta\pi\pi}{\eta'}. \quad (42)$$

Eq. (42) is just $(\mathrm{X}\rightarrow\eta 4\pi)$, where the factor of $\eta'\rightarrow\eta\pi\pi$ is the dominate channel to be considered (i.e., $B(\eta'\rightarrow\eta\pi\pi)\simeq 65\%$). In this view, the process of $(\mathrm{X}\rightarrow\eta 2\pi)$ will be almost forbidden and the $(\mathrm{X}\rightarrow\eta 4\pi)$ or $(\mathrm{X}\rightarrow\eta' 2\pi)$ would be most favorable, i.e.,

$$B(\mathrm{X}\rightarrow\eta' 2\pi)\gg B(\mathrm{X}\rightarrow\eta 2\pi). \quad (43)$$

Since $m_{\eta'}\gg m_{\eta}$, this is a very unusual result. This result comes from that X(1835) is a baryon-antibaryon bound state, and its decay is caused by N-$\bar{\mathrm{N}}$ annihilations.

5 Summary

In this talk, the main contents of Refs. [4, 5] have been revived with some commentary. The main conclusion of[4, 5] is that X(1835) can be thought as a baryonium described by the Skyrme model. There are two positive evidences: 1) There exist a classical N$\bar{\mathrm{N}}$-Skyrmion solution with about $\sim$10MeV binding energies in the model; 2) The decay of this Skymion-baryonium is caused by annihilation of p-$\bar{\mathrm{p}}$ inside X(1835) through the quantum tunneling effect, and hence the most favorable decay channels are $\mathrm{X}\rightarrow\eta 4\pi$ or $\mathrm{X}\rightarrow\eta' 2\pi$. These lead to reasonable interpreting the data of BES, and especially to useful prediction on the decay mode of X(1835) for the experiment.

It would be interesting to pursue the the semi-classical quantum corrections in the further works.

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References

1 BAI J Z et al(BES Collaboration). Phys. Rev. Lett., 2003, **91**: 022001
2 Fermi E, Yang C N. Phys. Rev., 1949, **76**: 1739
3 Datta A, O'Donnel P J. Phys. Lett., 2003, **B567**: 273
4 YAN Mu-Lin, LI Si, WU Bin, MA Bo-Qing. Phys. Rev., 2005, **D72**: 034027
5 DING Gui-Jun, YAN Mu-Lin. Phys. Rev., 2005, **C72**: 015208
6 DING Gui-Jun, YAN Mu-Lin. Baryon-Antibaryon Enhancements in Quark Models. hep-ph/0510013
7 GAO Chong-Shou, ZHU Shi-Lin. Commun. Theo. Phys., 2004, **42**: 844
8 Amado R D, Cannata F, Dedonder J P et al. Phys. Rev. Lett., 1994, **72**: 970
9 Amado R D, Cannata F, Dedonder J P et al. Phys. Rev., 1994, **C50**: 640—651
10 LU Yang, Amado R D. Phys. Lett., 1995, **B357**: 446; Phys. Rev., 1995, **C52**: 2158
11 Ablikim M et al(BES Collaboration). Phys. Rev. Lett., 2005, **95**: 262001
12 Eidelman S et al(Particle Data Group). Phys. Lett., 2004, **B952**: 1
13 ZOU B S, Chiang H C. Phys. Rev., 2004, **D69**: 034004
14 Sibirtsev A et al. Phys. Rev., 2005, **D71**: 054010
15 Skyrme T H R. Proc. Roy. Soc., 1961, **A260**: 127
16 Adkins G S, Nappi C R. Nucl. Phys., 1984, **B233**: 109
17 Witten E. Nucl. Phys., 1983, **B223**: 422 and 433
18 Jackson A, Jackson A D, Pasquier V. Nucl. Phys., 1985, **A432**: 567
19 Atiyah M F, Manton N S. Phys. Lett., 1989, **B222**: 438; Commun. Math. Phys., 1993, **153**: 422
20 Lacombe M, Loiseau B, Vinh Mau R et al. Phys. Rev., 1989, **D40**: 3012
21 SUN Z Y, CHEN K, YAN M L. Science in China, 1994, **A37**: 70
22 LI B A, YAN M L. Phys. Lett., 1992, **B282**: 435
23 Guadagnini E. Nucl. Phys., 1984, **B236**: 35; Manohar A V. Nucl. Phys., 1984, **B248**: 19; Chemtob M. Nucl. Phys., 1984, **B256**: 600; Praszalowicz M. Phys. Lett., 1985, **B158**: 264
24 YAN M L. Phys. Rev., 1987, **D35**: 2803; WU G W, YAN M L, LIU K F. Phys. Rev., 1991, **D43**: 185
25 Braaten E, Carson L. Phys. Rev. Lett., 1985, **56**: 1897
26 Schramm A J. Phys. Rev., 1988, **C37**: 1799
27 Atiyah M F, Manton N S. Phys. Lett., 1989, **B222**: 438; Commun. Math. Phys., 1993, **152**: 391
28 Leese R A, Manton N S, Schroers B J. Nucl. Phys., 1995, **B442**: 228
29 MA S. Rev. Mod. Phys., 1953, **25**: 853
30 Hulthen L, Sugawara M. Handbuch der Physik, 1959, **39**: 1
31 Schiff L I. Quantum Mechanics. McGraw-Hill Book Company, Inc., 1949
32 LU Y, Amado R D. Phys. Rev., 1996, **C54**: 1566
33 Maltman K, Isgur N. Phys. Rev., 1984, **D29**: 952
34 De Rujula A, Georgi H, Glashow S L. Phys. Rev., 1975, **D12**: 147
35 Sommermann H M, Seki R, Larson S et al. Phys. Rev., 1992, **D45**: 4303
36 SHAO B, Walet N R, Amado R D. Phys. Lett., 1993, **B303**: 1
37 Glauber R J. Phys. Rev., 1963, **130**: 2529; **131**: 2766. Glauber R J, Skagerstam B S. Coherent States. Singapore: World Scientific Publishing Co., 1985

X(1835): Skyrme模型中的质子–反质子束缚态*

闫沐霖[1)]

(中国科技大学交叉学科理论研究中心, 近代物理系　合肥　230026)

摘要　BES(北京谱仪)发现了奇特粒子态X(1835). 述评近年来把X(1835)解释为Skyrme模型中的$N\bar{N}$-重子偶素的工作. 有2个证据支持这种解释: 1) 存在$N\bar{N}$-经典Skyrmion解, 其结合能为$\sim$10MeV; 2) 这种Skyrmion-重子偶素的衰变是由X(1835)中的p-$\bar{p}$经由量子隧穿而湮没所引起的, 因此最可几的衰变道是X(1835)$\rightarrow\eta 4\pi$或X(1835)$\rightarrow\eta' 2\pi$. 这些导致了对BES实验数据的合理解释, 特别是关于X(1835)最可几的衰变模式的预言. 该预言对实验有价值.

关键词　奇特粒子态　质子–反质子束缚态　Skyrme模型　质子–反质子湮没　X(1835)衰变

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1) E-mail: mlyan@ustc.edu.cn